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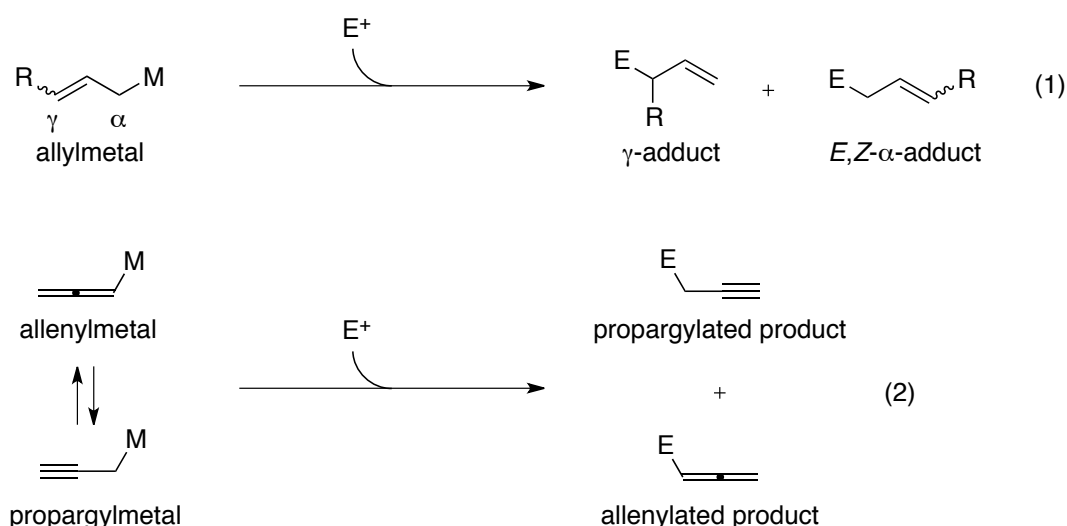
Abbreviations

<i>o</i>	ortho	Cp	cyclopentadienyl
<i>m</i>	meta	<i>E</i>	<i>entgegen</i> (means “opposite”)
<i>p</i>	para	<i>Z</i>	<i>zusammen</i> (means “together”)
<i>n</i>	normal	min	minute(s)
<i>c</i>	cyclo	h	hour(s)
<i>i</i>	iso	rt	room temperature (25 ± 3 °C)
<i>s</i> (<i>sec</i>)	secondary	°C	degrees Celsius
<i>t</i> (<i>tert</i>)	tertiary	d.r.	diastereo ratio
Me	methyl	equiv	equivalent(s)
Et	ethyl	cat.	catalytic
Pr	propyl	temp. (T)	temperature
Bu	butyl	mg	milligram(s)
Ph	phenyl	mL	milliliter(s)
Mes	mesityl	mmol	millimole
Cy	cyclohexyl	mm	millimeter(s)
Cyp	cyclopentyl	MPa	megapascal
TMS	trimethylsilyl	quant.	quantitative
TBS	<i>tert</i> -butyldimethylsilyl	NMR	nuclear magnetic resonance
TIPS	triisopropylsilyl	δ	chemical shift in parts per million downfield from tetramethylsilane
Ac	acetyl	s	singlet (spectral)
acac	acetylacetonate	d	doublet (spectral)
cod	1,5-cyclooctadiene	t	triplet (spectral)
dba	dibenzylidene acetone	q	quartet (spectral)
NMP	<i>N</i> -methylpyrrolidone	sept	septet (spectral)
DME	1,2-dimethoxyethane	m	multiplet (spectral), meter(s), milli
DMA	dimethylacetamide	br	broad (spectral)
dppp	1,3-bis(diphenylphosphino)propane	<i>J</i>	coupling constant (in NMR)
tol	tolyl	Hz	hertz (s ⁻¹)
Tf	trifluoromethanesulfonyl	MHz	megahertz
phen	1,10-phenanthroline	ppm	parts per million (in NMR)
THF	tetrahydrofuran	IR	infrared (spectrum)
PMB	<i>p</i> -methoxybenzyl	cm	centimeter(s)
DDQ	2,3-dichloro-5,6-dicyano- 1,4-benzoquinone	m.p.	melting point
DABCO	1,4-diazabicyclo[2.2.2]octane	calcd	calculated
DBU	1,8-diazabicyclo[5.4.0.]undec-7-ene	HRMS	high-resolution mass spectrum
IPr	bis(2,6-diisopropylphenyl)imidazol-2- ylidene	<i>R</i> _f	retention factor (in TLC)
SPhos	2-dicyclohexylphosphino-2',6'- dimethoxybiphenyl	TLC	thin-layer chromatography
Xphos	2-dicyclohexylphosphino-2',4',6'- triisopropylbiphenyl	EI	electron ionization
		ESI	electrospray ionization
		APCI	atmospheric pressure chemical ionization

General Introduction

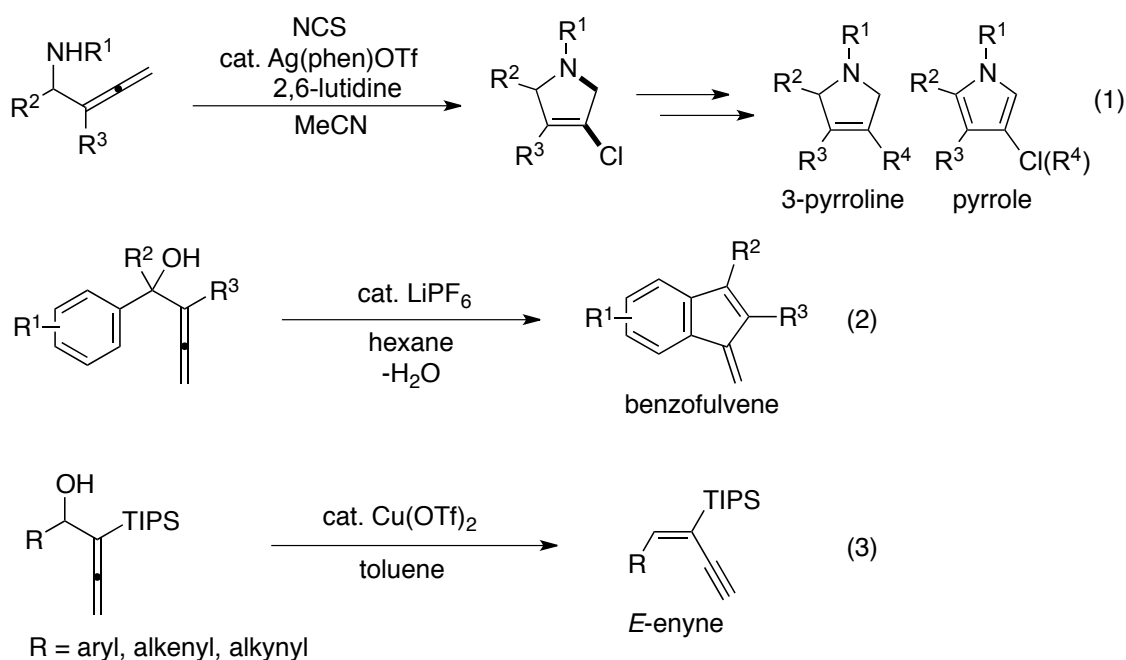
The allyl-, allenyl-, and propargylmetals have attracted much interest as a synthetic tool and have been intensively studied for many years. However, there are still several problems to be addressed. The most important issue in their reaction is to control the regioselectivity with electrophiles. For example, when a crotyl-type reagent reacts with electrophiles, α -adduct and γ -adduct can be obtained (Scheme 1, eq 1). In addition, α -adduct is usually composed of a mixture of *E/Z* isomers. Allenylmetals are generally in equilibrium with the corresponding propargylmetals. Thus, in the reaction with electrophiles such as carbonyl compounds, allenylated products and propargylated products can be formed (Scheme 1, eq 2). Therefore, controlling the regioselectivity in the reactions using allyl-, allenyl-, and propargylmetals still remains an important synthetic challenge, although many efforts have been made to solve the problem. In this context, the author has developed a copper-based catalyst system effective for the regioselective allylation, allenylation, and propargylation of carbonyls and imines.

Scheme 1.



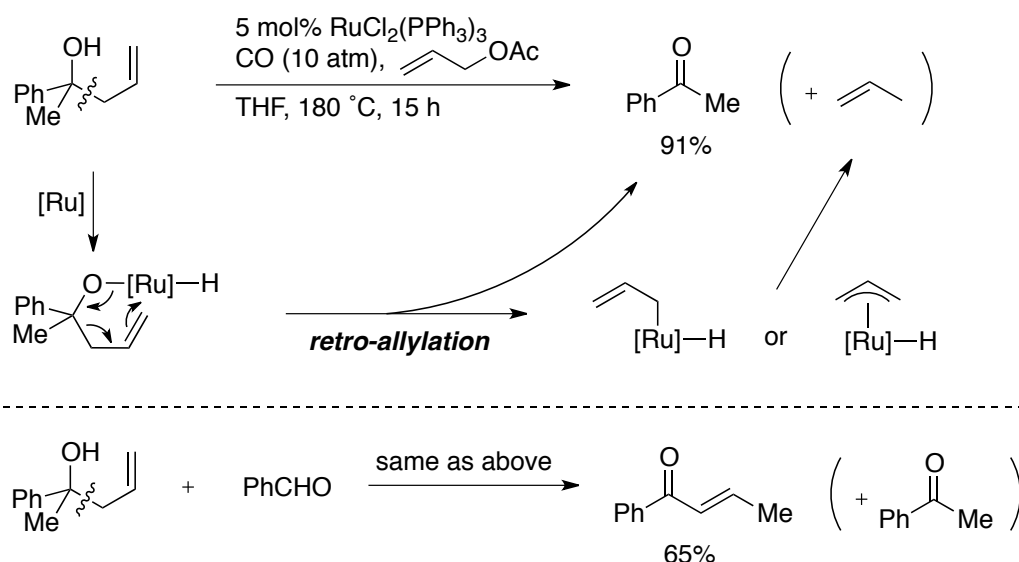
When the selective installation of allyl, allenyl, and propargyl groups to various electrophiles is achieved, transformations of these products would be more valuable. Thus, the author focused on the allenic compounds that had been obtained selectively, and discovered three types of reactions. The first is a silver-catalyzed intramolecular chloroamination of allenes (Scheme 2, eq 1). This reaction yields 3-pyrroline derivatives bearing an alkenyl chloride moiety, which can be easily converted into functionalized 3-pyrroline and pyrrole derivatives. The second is a Li^+ -catalyzed Nazarov-type cyclization of 1-aryl-2,3-butadien-1-ols (Scheme 2, eq 2). The obtained benzofulvenes possess a diverse range of potential applications in the material chemistry and are useful as precursors of indenyl ligands. The third is a copper-catalyzed stereoselective synthesis of functionalized conjugated enynes from α -allenols (Scheme 2, eq 3). This protocol is also applicable to the synthesis of conjugated dienyne and enediynes with excellent selectivity.

Scheme 2.

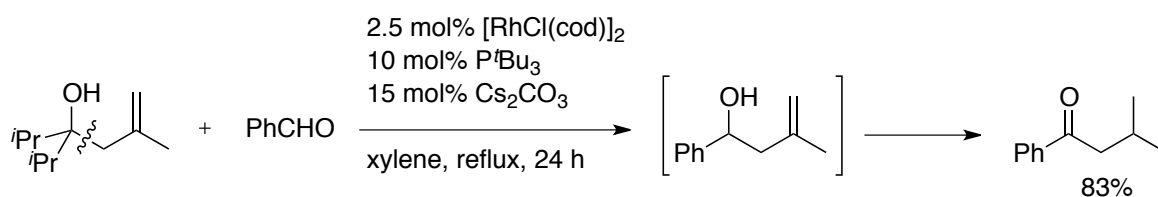


Allyl-, Allenyl-, and Propargyl-Transfer Reactions through Cleavage of C–C Bonds Catalyzed by an N-Heterocyclic Carbene/Copper Complex: Synthesis of Multisubstituted Pyrroles (Chapter 1)

Allylation of electrophiles by allylic metals is one of the most fundamental and important reactions in organic chemistry.¹ Various protocols for the preparation of allylic metals have been well investigated, including reductive metalation of allylic halides or pseudohalides by low-valent metal, transmetalation of highly reactive allylic metal to another metal, direct allylic deprotonation by strong base, hydrometalation (carbometalation) of allene, and allylic C–H bond activation of alkene. However, these methods usually suffer from some drawbacks such as poor functional group tolerance and undesired byproducts. Recently, new methods involving metal-catalyzed retro-allylation of homoallyl alcohols have been developed, which succeed in the generation and use of allylic metals under mild conditions. In 1998, Kondo and Mitsudo developed a pioneering ruthenium-catalyzed retro-allylation of *unstrained* tertiary homoallyl alcohols (Scheme 1-1).² They also succeeded in C–C bond forming reaction using in situ generated allylruthenium species. This reaction is believed to proceed via the oxidative addition of a hydroxyl group to a Ru catalyst followed by retro-allylation of the ruthenium alkoxide to afford acetophenone and propene. The driving force of this reaction might be the formation of a stable η^3 -allylruthenium species as an intermediate.

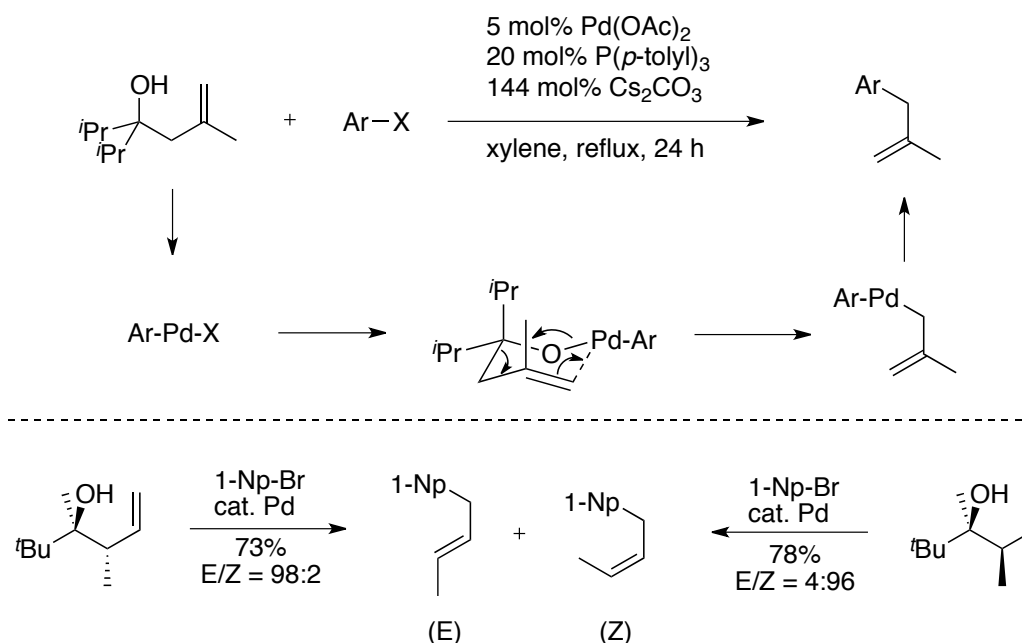
Scheme 1-1.

In 2006, Oshima accomplished a similar reaction by using a Rh catalyst (Scheme 1-2).³ In this case, saturated ketones were obtained as the final product by isomerization via iterative β -hydrogen elimination-hydorrhodation sequence.

Scheme 1-2.

Oshima applied this type of $\text{Csp}^3\text{--Csp}^3$ bond cleavage to allylation of aryl halides under palladium catalysis (Scheme 1-3).⁴ The Pd-catalyzed retro-allylation proceeds in a concerted fashion via a conformationally regulated six-membered cyclic transition state. As a result, the allylated product can be obtained with excellent regio- and stereoselectivity.

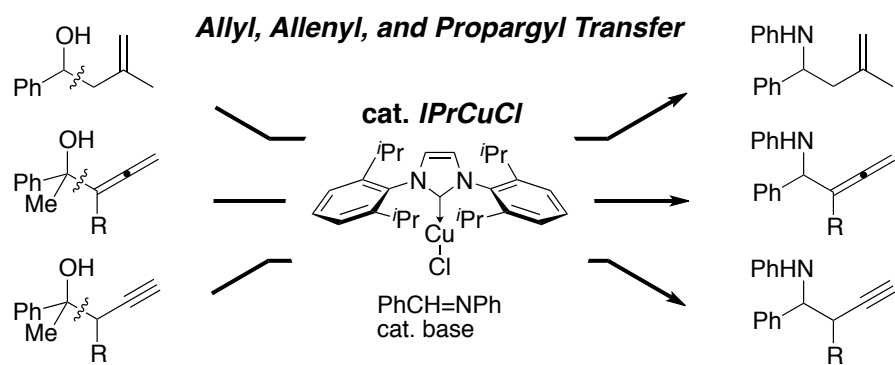
Scheme 1-3.



Although these reactions successfully employ tertiary homoallyl alcohols as the allyl donor, the use of secondary ones is difficult because the process always suffers from overwhelmingly smooth oxidation through β -hydrogen elimination from the corresponding metal alkoxides.⁵

In Chapter 1, the author reports a copper-catalyzed selective cleavage of Csp³–Csp³ bonds by retro-allylation of homoallyl alcohols including secondary ones (Scheme 1-4). In situ generated allylcopper species is applicable to catalytic allylation of aldehydes and imines. While copper can often replace palladium and rhodium in many catalytic bond-forming processes,⁶ the use of copper catalysts in catalytic C–C bond cleavage reactions has remained unexplored.⁷ This method can be also extended to the regioselective allenylation and propargylation of imines.⁸

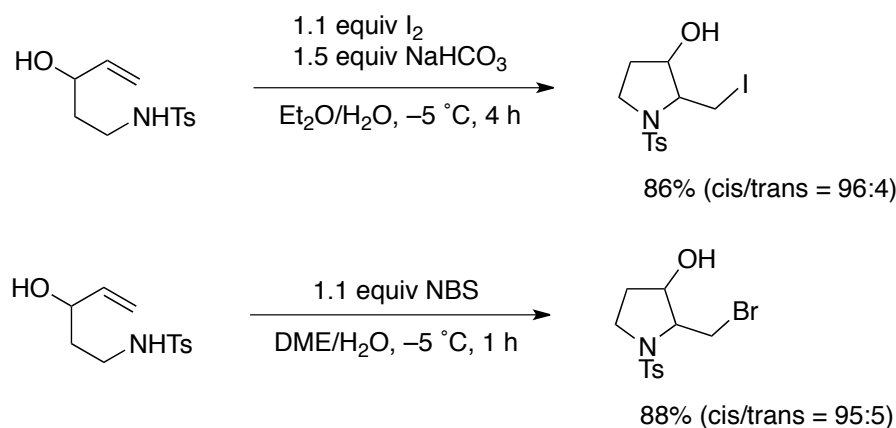
Scheme 1-4.



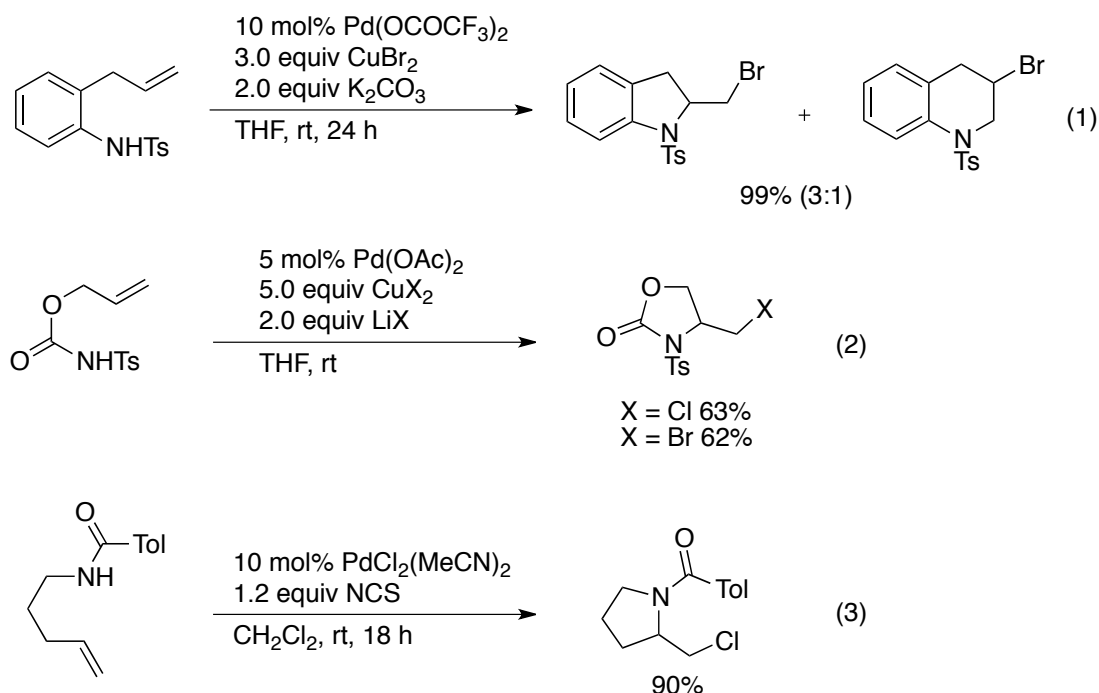
Silver-Catalyzed Intramolecular Chloroamination of Allenes: Easy Access to Functionalized 3-Pyrroline and Pyrrole Derivatives (Chapter 2)

The intramolecular haloamination of alkenes has emerged as a powerful tool for the construction of aza-cycles carrying halogen atoms at the β -position of the nitrogen.⁹ These cyclic vicinal haloamines have applications as potential medicinal agents but are primarily used as versatile synthetic intermediates.¹⁰ Thus, a facile and efficient method for the synthesis of cyclic vicinal haloamines has received much attention in recent years. Many traditional approaches to these compounds have been performed using relatively active halogen sources in the absence of metal catalysts. In 1984, Yoshida and Tamaru reported intramolecular iodoamidation and bromoamidation reactions of alkenes using I_2 or NBS as the halogen cation equivalents (Scheme 2-1).¹¹

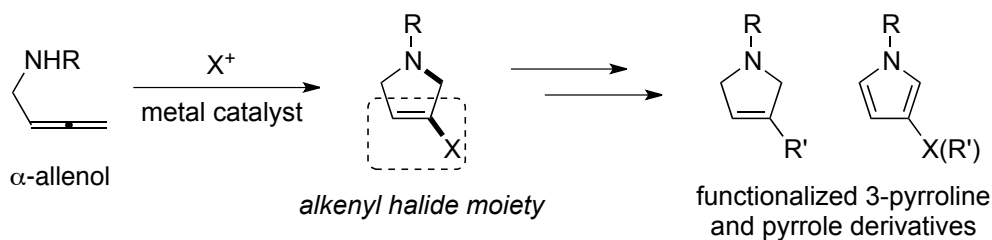
Scheme 2-1.



In recent years, transition-metal-catalyzed variants have been intensively investigated. In 2004, Chemler¹² and Lu¹³ independently described a Pd-catalyzed intramolecular haloamination of sulfonamidoalkenes using copper halides as the halogen source (Scheme 2-2, eqs 1 and 2). Michael also reported a Pd-catalyzed chloroamination of protected aminoalkenes with NCS as the chlorinating reagent (Scheme 2-2, eq 3).¹⁴ This cyclization reaction proceeds with high regioselectivity for 5-*exo* cyclization.

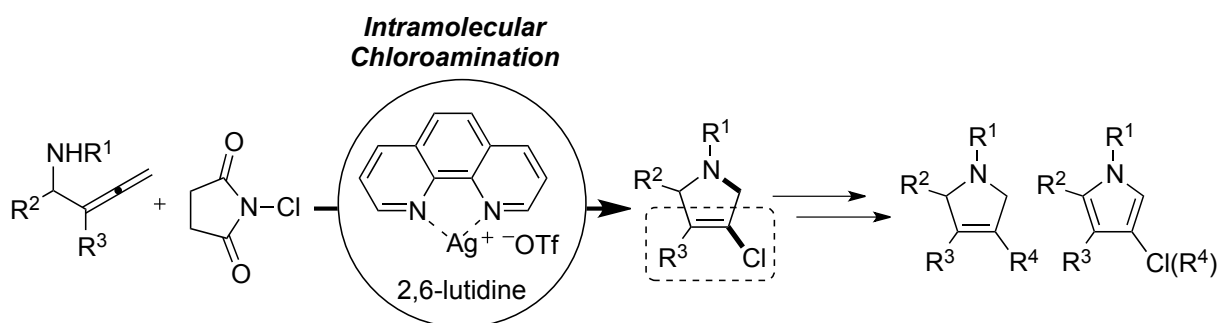
Scheme 2-2.

Compared to many examples of haloamination of alkenes, reactions of alkynes¹⁵ or allenes¹⁶ have hardly been investigated thus far. When the haloamination of α -aminoallene proceeds in a 5-*endo* manner, it yields a pyrroline derivative with a halogen on sp²-carbon (Scheme 2-3).¹⁷ The alkenyl halide moiety can be utilized for further transformations such as cross-coupling reactions. Furthermore, pyrrolines are readily converted to synthetically useful pyrrole derivatives. In this manner, the intramolecular haloamination of allenes are quite useful.

Scheme 2-3.

In Chapter 2, the author reports that a 1,10-phenanthroline-ligated cationic silver complex allows the intramolecular chloroamination of allenes with NCS and 2,6-lutidine as a base (Scheme 2-4). The chloroamination products are versatile synthetic intermediates and can be easily transformed into functionalized 3-pyrroline and pyrrole derivatives.

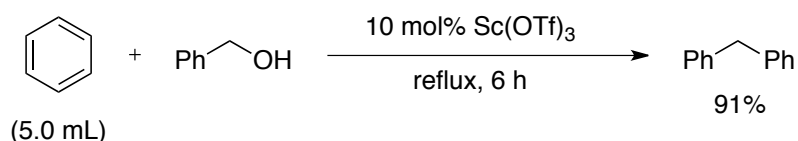
Scheme 2-4.



Li⁺-Catalyzed Nazarov-Type Cyclization of 1-Aryl-2,3-butadien-1-ols: Synthesis of Benzofulvene Derivatives (Chapter 3)

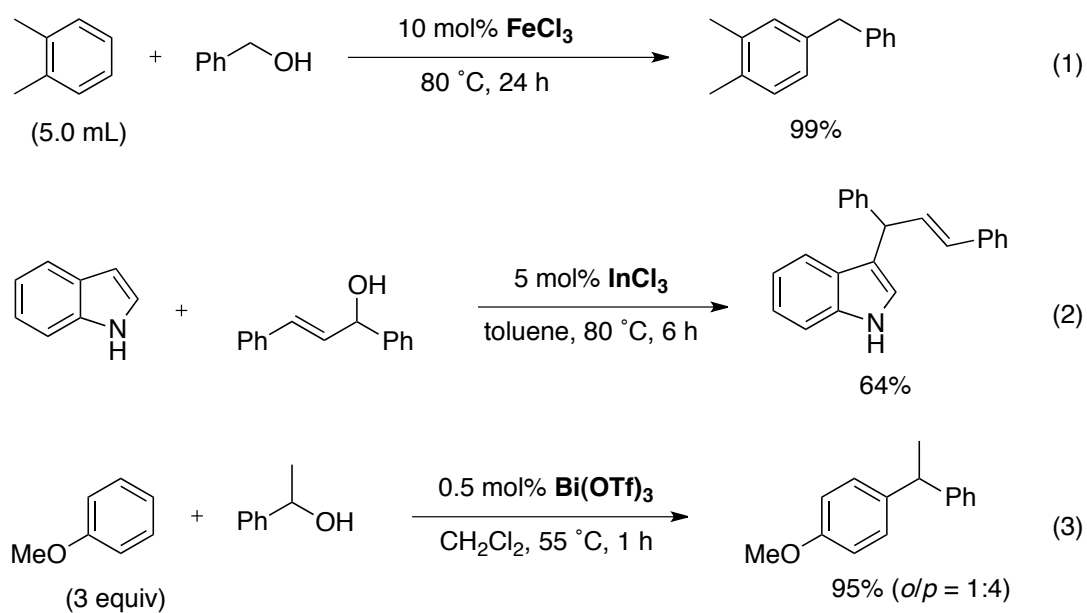
The alkylation of aromatic compounds is a synthetically useful transformation for the construction of carbon–carbon bonds.¹⁸ The vast majority of traditional methods has involved the use of alkyl halides and pseudohalides as alkylating reagents in the presence of Lewis acid catalysts. In terms of atom economy and environmental concerns, employment of alcohols as alkylating reagents is highly desirable. However, direct catalytic substitution of alcohols with arenes is often problematic: in addition to the poor leaving ability of the hydroxy group, alcohol substrates and/or in situ generated water can deactivate the catalyst. Therefore, much attention has been paid to developing the water resist Lewis acid catalysts being sufficient to activate the alcohol functionality. In 1996, Hiyama and Fukuzawa reported that Sc(OTf)₃ proved to be a quite effective catalyst for the benzylation of arenes with benzyl alcohols (Scheme 3-1).¹⁹ They also demonstrated the utility of lanthanide triflates such as Sm(OTf)₃, Nd(OTf)₃, and Yb(OTf)₃ for this type of reaction.²⁰

Scheme 3-1.



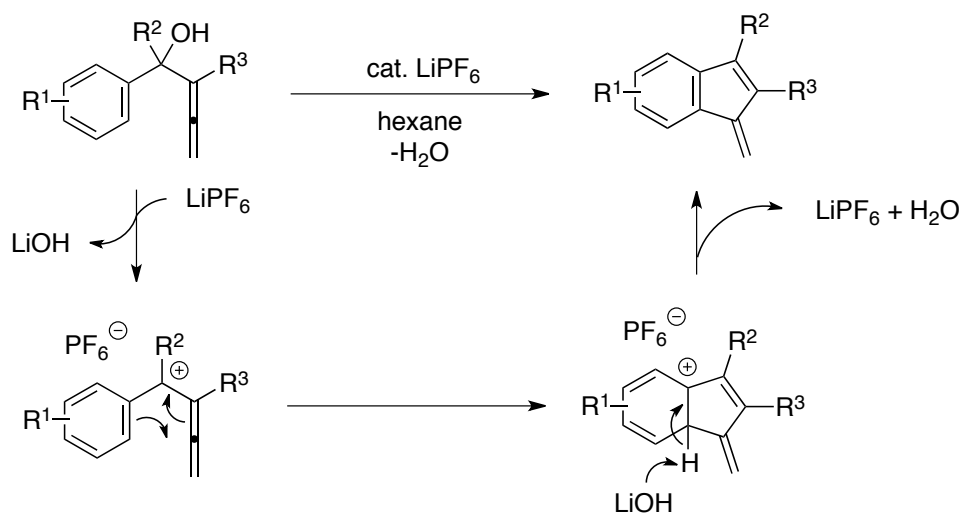
In 2005, Beller and co-workers disclosed an excellent iron-catalyzed benzylation reaction. Using 10 mol% of inexpensive FeCl₃, the addition of benzyl alcohols to *o*-xylene could be well performed (Scheme 3-2, eq 1).²¹ In 2006, Baba reported the allylation of indoles using allyl alcohols as allylating reagents catalyzed by InCl₃ (Scheme 3-2, eq 2).²² In the same year, Rueping developed a highly efficient Bi(OTf)₃-catalyzed benzylation of arenes and heteroarenes (Scheme 3-2, eq 3).²³ Recently, late transition metals such as Ag, Au, Pt, Ru, and Pd have also been utilized.²⁴

Scheme 3-2.



In Chapter 3, the author investigated the Lewis acidity of alkali metals and found that LiPF_6 was uniquely effective for the activation of the alcohol functionality.²⁵ Considering abundance, low cost, and nontoxicity of lithium salts, development of lithium-based catalyst systems would be worth investigation. He applied this strong oxophilic nature of LiPF_6 to the Nazarov-type cyclization of 1-aryl-2,3-butadien-1-ols, which afforded benzofulvene derivatives (Scheme 3-3).

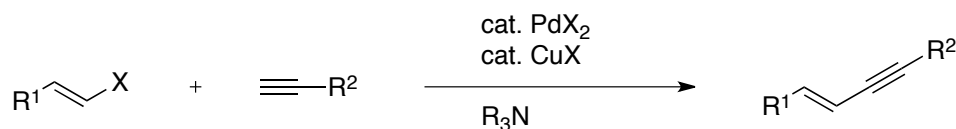
Scheme 3-3.



Copper-Catalyzed Stereoselective Synthesis of Functionalized Conjugated Enynes, Dienynes, and Eneidyne from α -Allenols (Chapter 4)

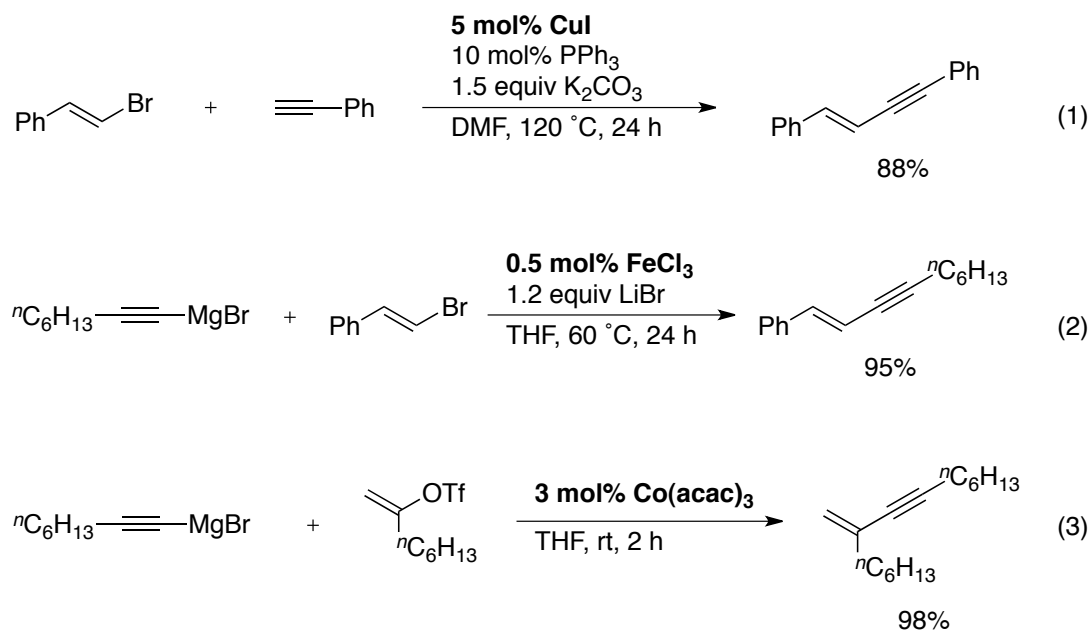
Conjugated enynes are important structures that serve as key components of a wide range of biologically active compounds, natural products, pharmaceuticals, and functional organic materials.²⁶ Due to the importance of this structural unit, many synthetic approaches have been developed. Among them, the most common and straightforward method is the Pd/Cu co-catalyzed cross-coupling of an alkenyl halide with a terminal alkyne, known as the Sonogashira reaction (Scheme 4-1).²⁷

Scheme 4-1.



Recently, many practical variations using less expensive metal catalysts have been intensively studied, which often accommodate substrates that are difficult to employ by the Pd-based protocols. For examples, in 1993, Nomura and Miura reported a copper-catalyzed cross-coupling reaction of vinyl halides with terminal alkynes in the absence of a Pd catalyst (Scheme 4-2, eq 1).^{28,29} Nakamura disclosed a iron-catalyzed coupling between vinyl halides and alkynyl Grignard reagents with the aid of lithium salts (Scheme 4-2, eq 2).^{30,31} Hayashi and Shirakawa also described a cobalt-catalyzed enyne coupling (Scheme 4-2, eq 3).³²

Scheme 4-2.

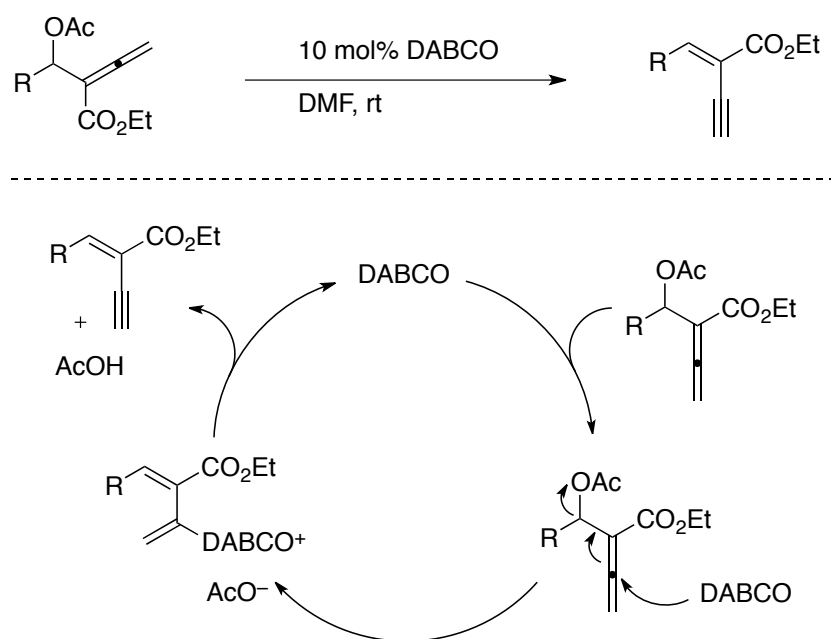


However, despite the great synthetic utility of this coupling approach, the stereocontrolled synthesis of conjugated enynes is somewhat difficult for several reasons: (1) the coupling reaction generally proceeds with retention of stereochemistry of alkenyl halides, requiring the use of stereodefined starting materials, (2) the partial loss of the stereochemical information of starting alkenyl halides is observed in some cases, and (3) functional groups such as carbon-halogen bonds are not compatible under low valent metal catalysis.

In 2009, Lee reported an alternative approach to stereochemically pure enynes from the treatment of allenyl acetates with DABCO (Scheme 4-3).³³ This Lewis-base catalyzed reaction is initiated by S_N2'-type displacement of allenyl acetate with DABCO, affording the vinylammonium salt as an intermediate. Subsequent elimination reaction of the intermediate produces the desired enyne and regenerates the DABCO catalyst to continue catalytic cycle. While this reaction proceeds with perfect *E* selectivity and high functional group tolerance, all substrates examined have an electron-withdrawing group on the allenyl moiety, which limits the synthetic utility. In addition, enynes having tetrasubstituted alkene moiety cannot be prepared by this method because acetylation of the corresponding tertiary alcohols does not proceed. As

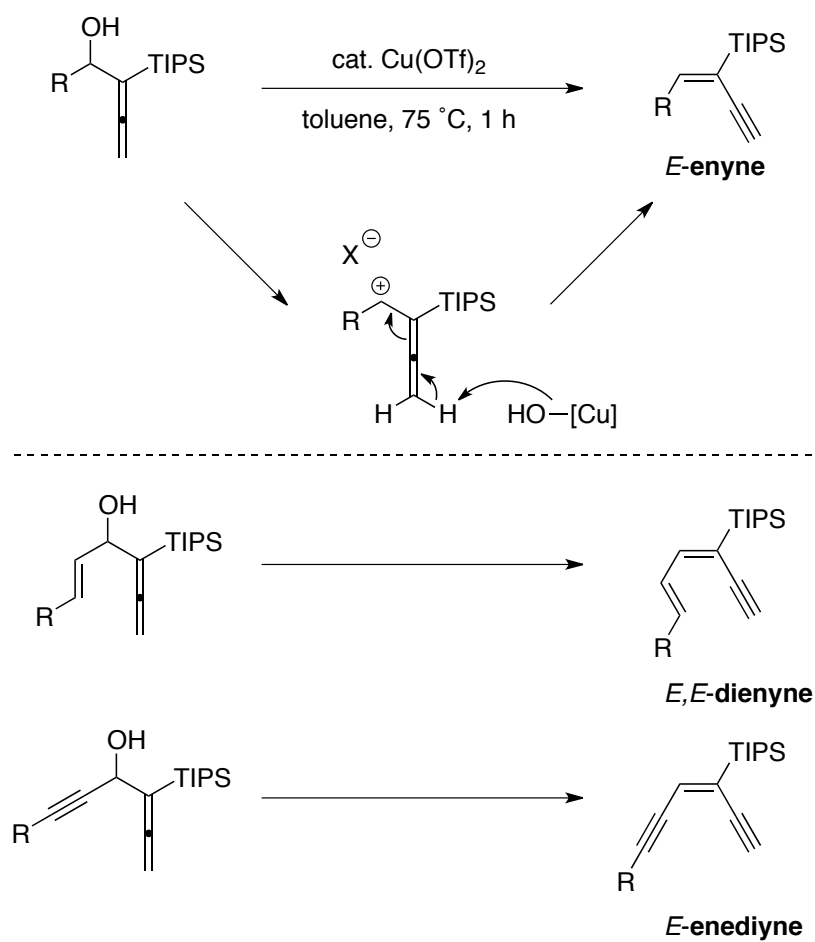
such, the development of a more practical method for the synthesis of stereochemically pure enynes remains an ongoing synthetic challenge.

Scheme 4-3.



In Chapter 4, the author describes a copper-catalyzed stereoselective synthesis of functionalized conjugated enynes from α -allenols, which enjoys a variety of functional groups (Scheme 4-4). Selective abstraction of the allenyl proton by a copper catalyst would be the key step to achieve this reaction. This protocol is also applicable to the synthesis of conjugated dienynes and enediynes with excellent stereoselectivity.

Scheme 4-4.



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Chapter 1

Allyl-, Allenyl-, and Propargyl-Transfer Reactions through Cleavage of C–C Bonds Catalyzed by an N-Heterocyclic Carbene/Copper Complex: Synthesis of Multisubstituted Pyrroles

An NHC-copper complex can promote C–C bond cleavage through retro-allylation of homoallyl alcohols to form allylcopper species. This process is applicable to catalytic allylation of aldehydes and imines with homoallyl alcohols. The method has also been extended to regioselective allenylation and propargylation of imines.

Introduction

Development of efficient methods for transition-metal-catalyzed selective cleavage of C–C bonds and their application has been a challenging subject of modern organic synthesis.¹ Recently, several research groups have developed transition-metal-catalyzed retro-allylation of homoallyl alcohols as a C–C bond-cleavage strategy and thus have succeeded in the generation and use of allylmetals under mild conditions.² However, expensive transition metals such as palladium, rhodium, and ruthenium were required in these reactions.³ Thus, it is more cost-efficient to replace such expensive transition-metal catalysts with cheaper ones. While copper can often replace palladium and rhodium in many catalytic bond-forming processes, use of this cheaper and ubiquitous alternative in catalytic C–C bond cleavage reactions has remained unexplored. In Chapter 1, the author reports a retro-allylation of homoallyl alcohols and allylation reaction of carbonyl compounds catalyzed by an NHC-Cu complex.⁴ This catalyst system is also applicable to allenylation and propargylation of imines—a process that provides synthetically useful allenic amines or homopropargyl amines with excellent selectivity. These products can be transformed into valuable five-membered azacycles such as 2-pyrroline, 3-pyrroline, and pyrrole derivatives.

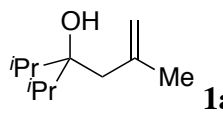
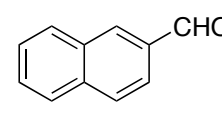
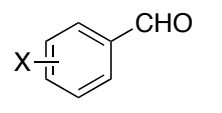
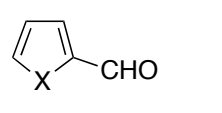
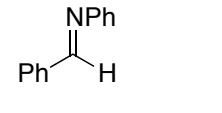
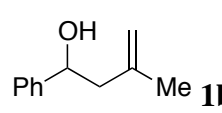
Results and Discussion

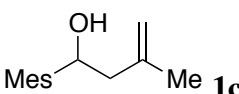
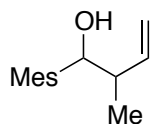
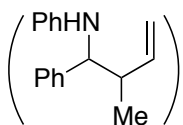
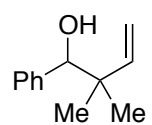
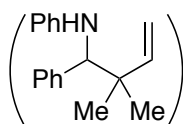
Treatment of 2-naphtaldehyde (**2a**) with homoallyl alcohol **1a** in the presence of a catalytic amount of Cu(IPr)Cl and NaO'Bu in refluxing toluene for 2 h afforded the methallylated product **3a** in good yield (Table 1, entry 1). Electron-rich aldehydes successfully underwent the allylation (Table 1, entries 2–4). The reaction of electron-poor 4-fluorobenzaldehyde gave a moderate yield of **3e** (Table 1, entry 5). Steric hindrance around the carbonyl functionality did not significantly retard the allylation (Table 1, entries 6 and 7). Heteroaromatic aldehydes were also suitable substrates (Table 1, entries 8 and 9). Selective 1,2-addition occurred in the reaction

of cinnamaldehyde with alcohol **1a** (Table 1, entry 10).

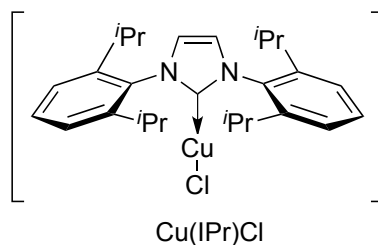
This allyl transfer is applicable to the allylation of an imine (Table 1, entry 11). Remarkably, the present catalytic system has proved to be effective for allyl transfer from secondary homoallyl alcohols (Table 1, entries 12–15). Metal-mediated retro-allylation of secondary homoallyl alcohols is difficult because the process always suffers from overwhelmingly smooth oxidation through β -hydrogen elimination from the corresponding metal alkoxides. To the best of our knowledge, this represents the first example of catalytic allyl transfer reaction by retro-allylation using secondary homoallyl alcohols as allyl donors.⁵

Table 1. Allylation of Aldehydes and Imines with Homoallyl Alcohols Catalyzed by Cu(IPr)Cl

$ \begin{array}{c} \text{R}^1 \text{---} \text{C} \text{---} \text{OH} \\ \\ \text{R}^2 \text{---} \text{C} \text{---} \text{C} \text{---} \text{R}^5 \\ \quad \\ \text{R}^3 \quad \text{R}^4 \end{array} + \text{Ar} \text{---} \text{C} \text{---} \text{H} \xrightarrow[\text{toluene, reflux, 2 h}]{\text{cat. Cu(IPr)Cl, cat. NaO}^t\text{Bu}} \begin{array}{c} \text{XH} \\ \\ \text{Ar} \text{---} \text{C} \text{---} \text{C} \text{---} \text{R}^5 \\ \quad \\ \text{R}^3 \quad \text{R}^4 \end{array} $ <p>1 (1.2 equiv) X = O, NPh</p>							
entry	alcohol	electrophile	Cu/base (mol%)		yield (%) ^a		
1	 1a	 2a	1.0/5.0		3a	71	
							
2	1a	X = 4-Me	2b	1.0/5.0	3b	82	
3	1a	X = 4-OMe	2c	1.0/5.0	3c	93	
4	1a	X = 4-NMe ₂	2d	1.0/5.0	3d	79 ^b	
5	1a	X = 4-F	2e	2.0/6.0	3e	63	
6	1a	X = 2-Me	2f	2.0/6.0	3f	97 ^c	
7	1a	X = 2,4,6-Me ₃	2g	2.0/6.0	3g	92 ^c	
							
8	1a	X = O	2h	1.0/5.0	3h	71	
9	1a	X = S	2i	2.0/6.0	3i	65	
10	1a	Ph-CH=CH-CHO	2j	1.0/5.0	3j	88	
11	1a	 4a	1.0/5.0		5a	99	
12	 1b		4a	10/20	5a	77 ^d	

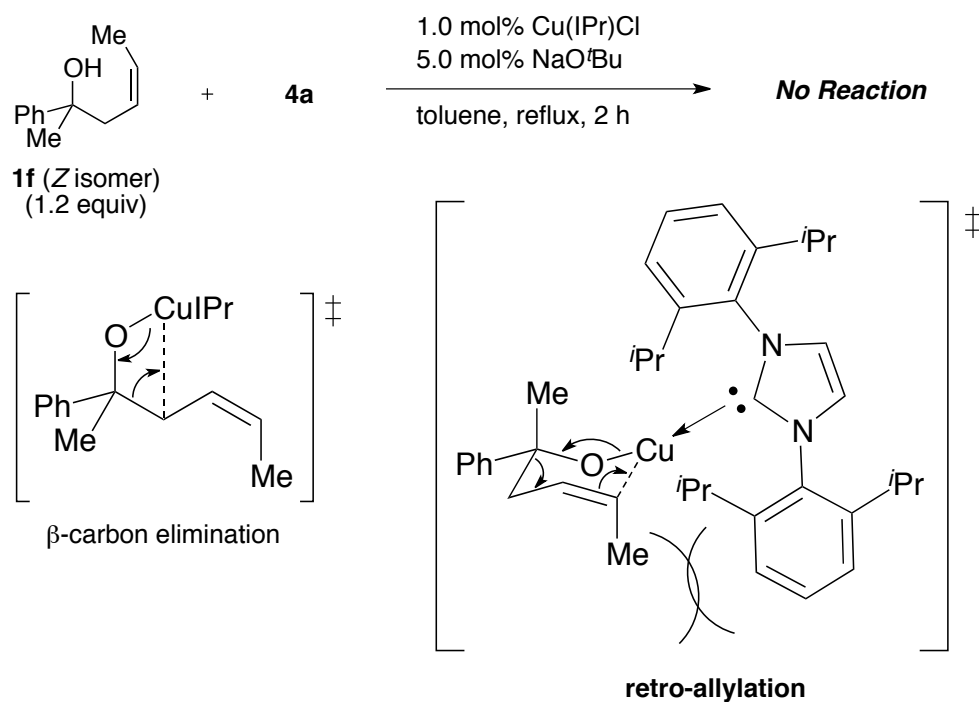
13		1c	4a	5.0/10	5a	94
14 ^e		1d	4a	5.0/10		5b 90
15		1e	4a	7.5/15		5c 80 ^f

^a Yield is of isolated product. ^b For 1 h with **1a** (1.5 equiv). ^c For 12 h. ^d For 9 h with **1b** (2.0 equiv). ^e For 3 h. **1d** : syn/anti = 1.2 : 1. **5b** : syn/anti = 1.9 : 1. ^f For 6 h.



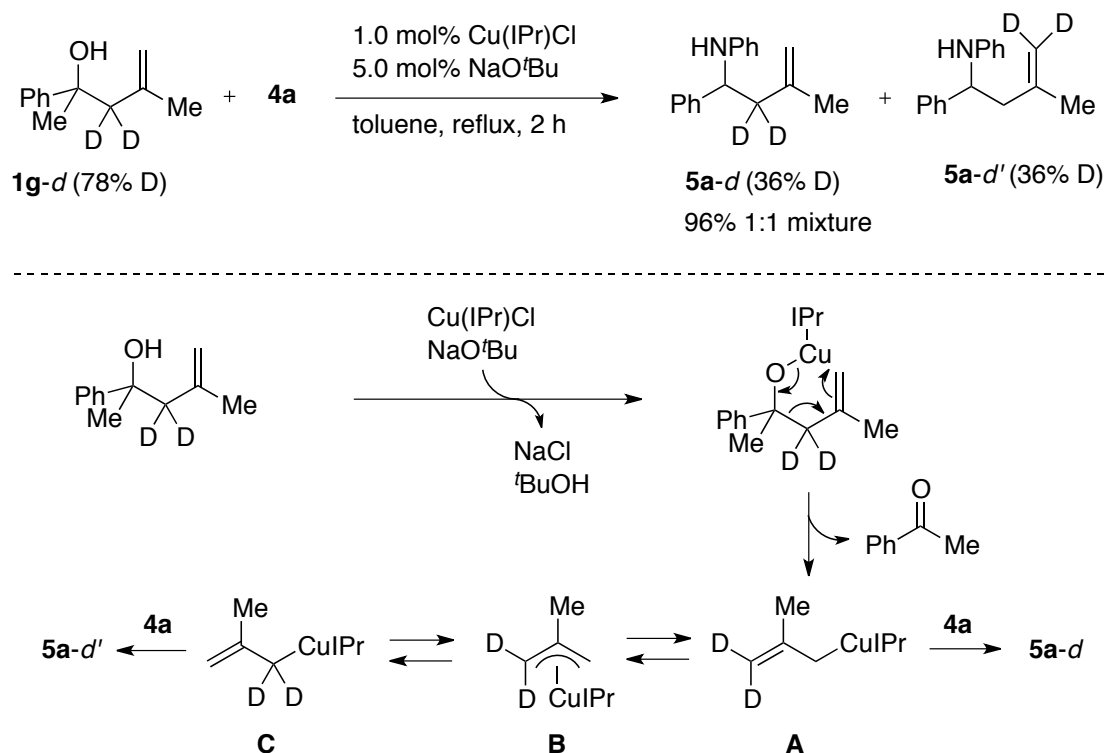
To gain insight into the mechanism, the author conducted the following experiments. When homoallyl alcohol **1f** bearing a methyl group at the olefin terminus was used, no reaction occurred (Scheme 1). This result indicates that on the transition state of the current reaction, the methyl group and the bulky carbene ligand would create so strong steric repulsion that the copper can not interact with the C–C double bonds. Thus, this reaction proceeds via six-membered transition state (retro-allylation), not four-membered transition state (β -carbon elimination).

Scheme 1.



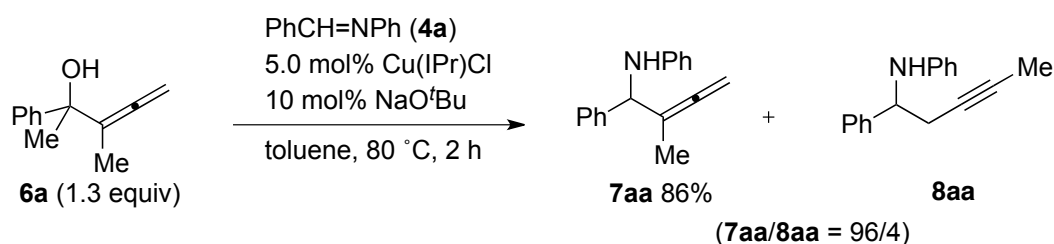
Next, the author performed labeling experiments by subjecting deuterated substrate **1g-d** (76% D contents at the allylic position) to the typical reaction conditions (Scheme 2). After the reaction was finished, the resulting deuterated products **5a-d** (38% D at the α -position) and **5a-d'** (38% D at the γ -position) were observed. This observation can be explained by assuming that the σ -allylcopper **A**, generated via retro-allylation of the copper alkoxide, is isomerized to σ -allylcopper **C** through π -allylcopper **B**.

Scheme 2.

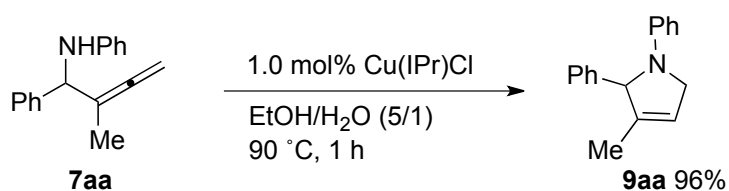


Encouraged by the success of the allylation reaction catalyzed by Cu(IPr)Cl, the author next applied this catalytic system to allenylation and propargylation of imines. Pleasingly, the reaction of allenic alcohol **6a** with imine **4a** proceeded to afford allenylated product **7aa** in excellent yield (Scheme 3). Intriguingly, the reaction exhibited high selectivity in favor of the formation of **7aa** (**7aa**/**8aa** = 96:4). Allenylmetal species are generally in equilibrium with the corresponding propargylmetal.⁶ Therefore, controlling the regioselectivity in the reactions using allenyl- and propargyl-metals remains an important challenge in organic synthesis.⁷ When the crude product containing **7aa** was heated in aqueous ethanol before chromatographic purification, **7aa** was converted into 3-pyrroline **9aa** (Table 2, entry 1). Notably, purified **7aa** did not isomerize into **9aa** under the same reaction conditions. The author eventually found that Cu(IPr)Cl was also highly effective for the cyclization to **9aa** (Scheme 4) as well as the allenyl transfer reaction. Although Au, Ag, and Pd are known to catalyze similar cyclization of 2,3-alkadienylamines,⁸ its copper-catalyzed variant has not been reported so far.

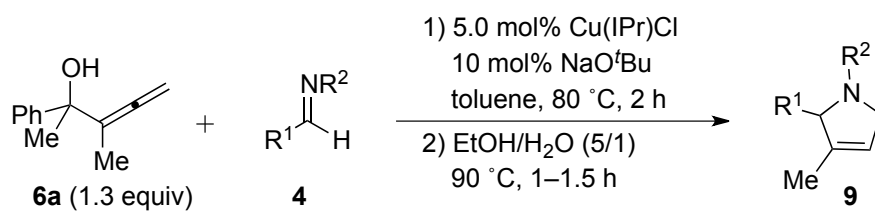
Scheme 3.



Scheme 4.



3-Pyrroline units are prominent structural motifs in natural products, and straightforward methods for their preparation should to be explored.^{8,9} The author therefore investigated the utility of the copper-catalyzed allenylation/cyclization for synthesizing 3-pyrrolines **9** (Table 2). The electronic nature of benzimine substrates does not significantly affect the reaction efficiency (Table 2, entries 1–6). The reaction tolerates a variety of functional groups such as keto, ester, and cyano (Table 2, entries 4–6). Carbon–halogen bonds could also survive, and are useful for further elaboration of the products (Table 2, entries 7–9). In addition, *N*-alkyl imine **4j** was also a suitable substrate to yield **9aj** in good yield (Table 2, entry 10).

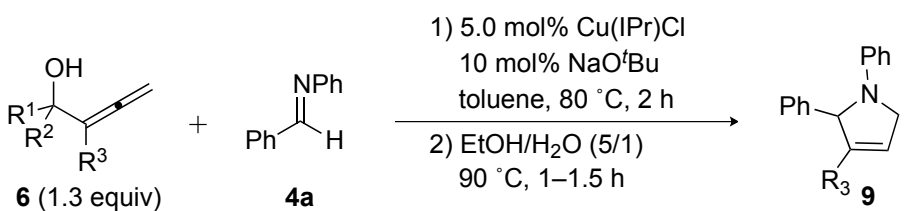
Table 2. Allenylation/Cyclization to 3-Pyrrolines Catalyzed by Cu(IPr)Cl

entry	imine 4		yield of 9 (%) ^a	
1	4a	R ³ = H	9aa	80
2 ^b	4b	R ³ = OMe	9ab	76
3	4c	R ³ = CF ₃	9ac	88
4	4d	R ³ = CO ^t Bu	9ad	87
5	4e	R ³ = CO ₂ Me	9ae	72
6	4f	R ³ = CN	9af	(97) ^c
7	4g	R ⁴ = Cl	9ag	90
8	4h	R ⁴ = Br	9ah	88
9	4i	R ⁴ = I	9ai	91
10 ^d	4j		9aj	68

^a Yield is of isolated product. ^b At 90 °C with **6a** (2.0 equiv). ^c Determined by ¹H NMR spectroscopy. ^d At reflux with **6a** (2.0 equiv).

Next, the scope of allenic alcohols was explored (Table 3). Allenic alcohols bearing an alkyl-, aryl-, or silyl-substituted allene moiety all worked well, and provided **9** in good yields. In the case of **6d**, 3-pyrroline **9da** containing a versatile vinylsilane moiety was obtained (Table 3, entry 3). Secondary allenic alcohol also reacted efficiently (Table 3, entry 4).

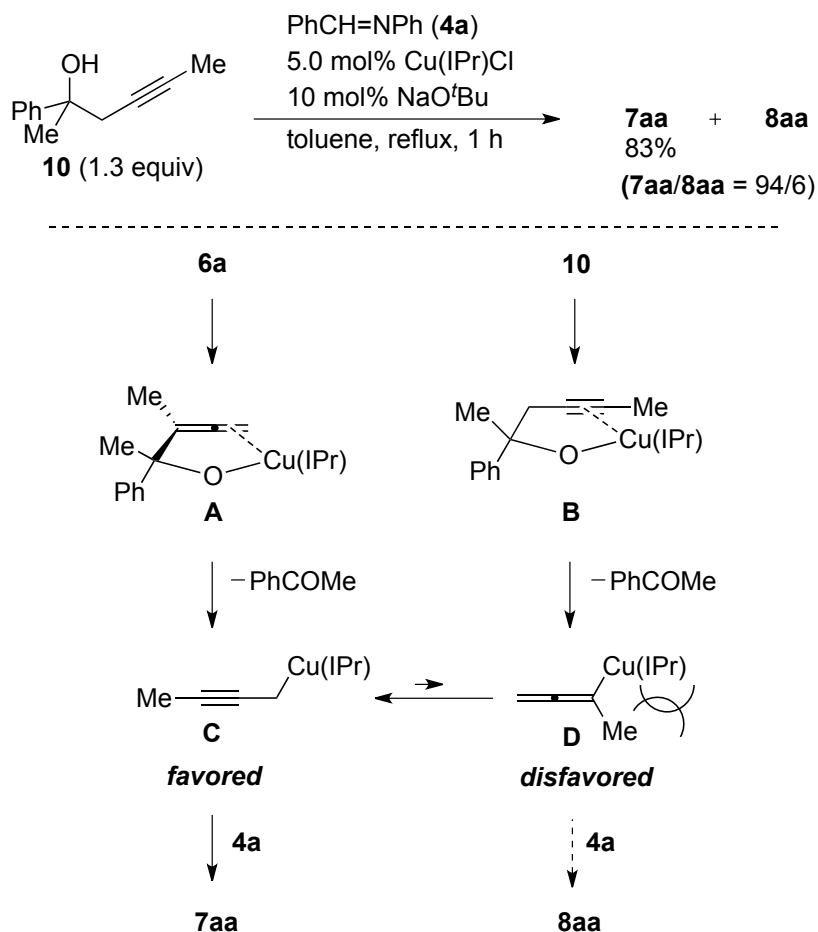
Table 3. Scope of Allenic Alcohols

					
entry		allenic alcohol			yield of 9 (%) ^a
		R ¹	R ²	R ³	
1	6b	Ph	Me	ⁿ Bu	9ba 81
2	6c	Ph	Me	Ph	9ca 79
3 ^b	6d	Ph	Me	SiMe ₃	9da 66
4 ^c	6e	Mes	H	Me	9aa 72

^a Yield is of isolated product. ^b Cu(IPr)Cl (10 mol %), NaOtBu (20 mol %), and **6d** (2.0 equiv) were used in the allenylation step, while Ag(phen)OTf (10 mol %) was used in the cyclization step. ^c At reflux for allenylation.

To gain insight into the mechanism and the high allenyl selectivity, homopropargyl alcohol **10** was subjected to the standard reaction conditions (Scheme 5). Interestingly, the predominant product was again **7aa**, which was the same product derived from **6a** (Scheme 3). This result can be explained as follows: allenylcopper **D**, generated by retro-propargylation¹⁰ of intermediate **B**, is less stable owing to steric repulsion between the methyl group and the bulky NHC. Accordingly, isomerization of **D** occurs to afford more stable propargyl copper **C**, which then reacts with imine **4a** to furnish **7aa**.

Scheme 5.



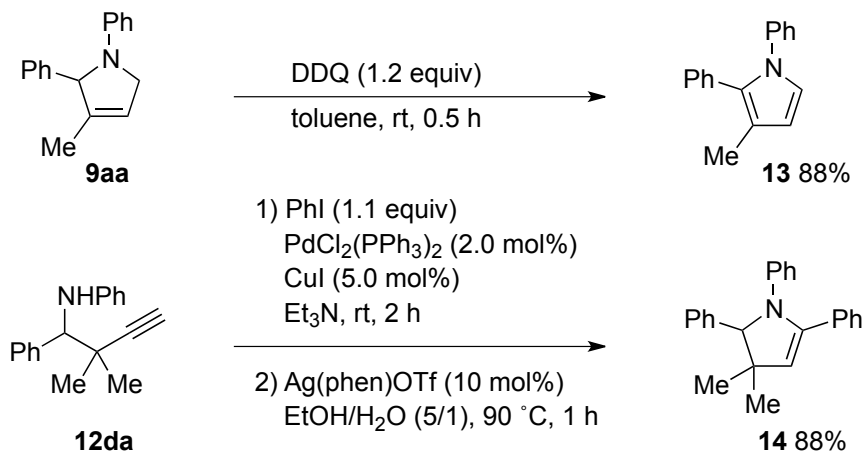
Homopropargyl alcohol **11a** bearing a methyl group at the propargyl position led to complete reversal of regioselectivity, and homopropargylamine **12aa** was exclusively formed (Table 4, entry 1). The effect of the substituent at the propargyl position is general (Table 4, entries 2–5). The bulky NHC would shift the allenyl–propargyl equilibrium toward allenylcopper, thus resulting in the propargylation of imines. In some cases, the reaction proceeded under milder reaction conditions (25 to 50 °C).

Table 4. Propargylation of Imine **4a** with Various Homopropargyl Alcohols Catalyzed by Cu(IPr)Cl

entry		alcohol		T (°C)	yield (%) ^a		d.r. ^b
		R ¹	R ²				
1	11a^c	Me	H	80	12aa	96	3.3:1
2	11b^c	C ₅ H ₁₁	H	80	12ba	quant.	4.6:1
3	11b^c			50	12ba	90	4.6:1
4	11c^d	Ph	H	25	12ca	94 ^e	1.2:1
5	11d	Me	Me	80	12da	98	—

^a Yield is of isolated product. ^b Determined by ¹H NMR spectroscopy. ^c Syn isomer. ^d d.r. = 1.1:1.^e With **11c** (1.5 equiv).

In addition to 3-pyrrolines, other important azacycles could be easily prepared (Scheme 6). Oxidation of 3-pyrroline **9aa** mediated by DDQ cleanly provided pyrrole **13**. Homopropargylamine **12da** also underwent the Sonogashira cross-coupling reaction¹¹ and subsequent silver-catalyzed cyclization¹² to yield 2-pyrroline¹³ **14** in 88 % yield.

Scheme 6.

Conclusion

The author has developed a retro-allylation of homoallyl alcohols and allylation reaction of carbonyl compounds catalyzed by a NHC–Cu complex, namely Cu(IPr)Cl. Cleavage of C(sp³)–C(sp³) bond through retro-allylation by the copper catalyst is the key step. The author has also applied this method to selective allenylation and propargylation of imines—a process that provides synthetically useful allenic amines or homopropargyl amines with excellent selectivity. These products can also be transformed into valuable five-membered azacycles such as 2-pyrroline, 3-pyrroline, and pyrrole derivatives.

Experimental Section

Instrumentation

^1H NMR (500 MHz) and ^{13}C NMR (125.7 MHz) spectra were taken on a Varian UNITY INOVA 500 spectrometer. Chemical shifts (δ) are in parts per million relative to tetramethylsilane at 0.00 ppm for ^1H and relative to CDCl_3 at 77.23 ppm for ^{13}C unless otherwise noted. Mass spectra were determined on a JEOL Mstation 700 spectrometer. IR spectra were determined on a SHIMADZU FTIR-8200PC spectrometer. Silica gel (Wakogel 200 mesh) was used for column chromatography. The analyses were carried out at the Elemental Analysis Center of Kyoto University.

Materials

Materials were obtained from commercial suppliers and purified by the standard procedures unless otherwise noted. Sodium *tert*-butoxide was purchased from Tokyo Chemical Industry Co., Ltd. and stored in desiccators. Toluene was purchased from Wako Chemical Co. and dried over slices of sodium. EtOH (dehydrated) was purchased from Wako Chemical Co. $\text{IPr}\cdot\text{HCl}$,¹⁴ IPrCuCl ,¹⁵ and $\text{Ag}(\text{phen})\text{OTf}$ ¹⁶ were prepared according to the reported method.

Allenic alcohols **6** were prepared according to the known procedure.^{7a} Aldimines **4** were prepared from the corresponding aldehydes and amines via classical dehydration reaction. Homopropargyl alcohols **11**, except **10**, were prepared according the literature.^{7a} Homopropargyl alcohol **10** was prepared by the reaction of acetophenone and 2-butyneImagnesium bromide. Homopropargyl alcohol **10** was separated from allenic alcohol **6a** after careful purification by column chromatography.

Experimental Procedures

Representative Procedure for NHC-Cu-Catalyzed Allylation of Aldehydes.

Compound 3a: Cu(IPr)Cl (2.4 mg, 0.0050 mmol) and NaO'Bu (2.4 mg, 0.025 mmol) were placed in a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, to the flask was added a solution of homoallyl alcohol **1a** (102.2 mg, 0.60 mmol) and 2-naphthaldehyde (**2a**) (78.1 mg, 0.50 mmol) in toluene (3.0 mL). Then the reaction mixture was heated at reflux for 2 h. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and NH₄Cl aq (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 5:1) to give **3a** (75.0 mg, 71%) as a white solid.

Procedure for NHC-Cu-Catalyzed Allenylation of Imine 4a.

Compound 7aa: Cu(IPr)Cl (12.0 mg, 0.025 mmol) and NaO'Bu (4.8 mg, 0.050 mmol) were placed in a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, to the flask was added a solution of allenic alcohol **6a** (113.3 mg, 0.65 mmol) and aldimine **4a** (90.6 mg, 0.50 mmol) in toluene (3.0 mL). Then the reaction mixture was heated at 80 °C for 2 h. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and NH₄Cl aq (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 40:1) to give **7aa** (100.8 mg, 86%) as a colorless oil.

Procedure for NHC-Cu-Catalyzed Cyclization of Allenylamine 7aa.

Cu(IPr)Cl (2.4 mg, 0.0050 mmol) was placed in a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, to the flask were added a solution of allenic amine **7aa** (117.7 mg, 0.50 mmol) in ethanol (2.5 mL) and water (0.5 mL). Then the

reaction mixture was heated at 90 °C for 1 h. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and brine (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 40:1) to give **9aa** (112.5 mg, 96%) as a white solid.

Representative Procedure for NHC-Cu-Catalyzed Sequential Allenylation/Cyclization of Imines.

Compound 9aa: Cu(IPr)Cl (12.0 mg, 0.025 mmol) and NaO^tBu (4.8 mg, 0.050 mmol) were placed in a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, to the flask was added a solution of allenic alcohol **6a** (113.3 mg, 0.65 mmol) and aldimine **4a** (90.6 mg, 0.50 mmol) in toluene (3.0 mL). Then the reaction mixture was heated at 80 °C for 2 h. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and NH₄Cl aq (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered. The filtrate was concentrated. A solution of the crude mixture in ethanol (2.5 mL) and water (0.5 mL) were added to a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser, and the mixture was heated at 90 °C for 1.5 h. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and brine (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 40:1) to give **9aa** (94.5 mg, 80%) as a white solid.

Procedure for NHC-Cu-Catalyzed Allenylation of 4a with 10.

Cu(IPr)Cl (12.0 mg, 0.025 mmol) and NaO'Bu (4.8 mg, 0.050 mmol) were placed in a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, to the flask was added a solution of homopropargyl alcohol **10** (113.3 mg, 0.65 mmol) and aldimine **4a** (90.6 mg, 0.50 mmol) in toluene (3.0 mL). Then the reaction mixture was heated at reflux for 1 h. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and NH₄Cl aq (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 40:1) to give **7aa** (97.3 mg, 83%) as a colorless oil.

Representative Procedure for NHC-Cu-Catalyzed Propargylation of Imines.

Compound 12aa: Cu(IPr)Cl (12.0 mg, 0.025 mmol) and NaO'Bu (4.8 mg, 0.050 mmol) were placed in a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, to the flask was added a solution of homopropargyl alcohol **11a** (113.3 mg, 0.65 mmol, single diastereomer) and aldimine **4a** (90.6 mg, 0.50 mmol) in toluene (3.0 mL). Then the reaction mixture was heated at 80 °C for 2 h. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and NH₄Cl aq (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 40:1) to give **12aa** (113.4 mg, 96%, d.r. = 3.3/1) as a colorless oil.

Procedure for Transformation of 9aa into 13.

2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (136.2 mg, 0.60 mmol) was placed in a vial tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube was added a solution of **9aa** (117.7 mg, 0.50 mmol) in toluene (3.0 mL), and the mixture was stirred for 30 min at room temperature. The mixture was passed through a short

activated alumina column with CH_2Cl_2 and concentrated. The residue was purified by column chromatography on silica gel (hexane/EtOAc, 20:1) to give **13** (102.9 mg, 88%) as a colorless oil.

Procedure for Transformation of **12da** into **14**.

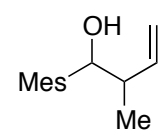
$\text{PdCl}_2(\text{PPh}_3)_2$ (7.0 mg, 0.010 mmol) and CuI (4.8 mg, 0.025 mmol) were placed in a vial tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube was added a solution of **12da** (124.7 mg, 0.50 mmol) and iodobenzene (112.2 mg, 0.55 mmol) in triethylamine (1.0 mL), and the mixture was stirred for 2 h at room temperature. The mixture was passed through a short activated alumina column with CH_2Cl_2 and concentrated.

$\text{Ag}(\text{phen})\text{OTf}$ (21.9 mg, 0.050 mmol) was placed in a dry 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, a solution of the crude mixture in ethanol (2.5 mL) and water (0.5 mL) were added to the flask, and the mixture was stirred for 1 h at 90 °C. After the mixture was cooled to room temperature, ethyl acetate (5 mL) and brine (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na_2SO_4 and filtered with Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 40:1) to give **14** (143.9 mg, 88%).

Characterization Data for New Compounds

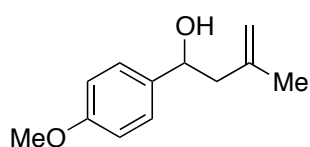
1-Mesityl-2-methyl-3-buten-1-ol (**1c**)

(50:50 mixture of two diastereomers)

 IR (neat) 3448, 2962, 1612, 1458, 1373, 1296, 1003, 918 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.80 (d, $J = 7.0$ Hz, $0.50 \times 3\text{H}$), 1.27 (d, $J = 6.5$ Hz, $0.50 \times 3\text{H}$), 1.74 (d, $J = 3.0$ Hz, $0.50 \times 1\text{H}$), 1.94 (d, $J = 2.0$ Hz, $0.50 \times 1\text{H}$), 2.237 (s, $0.50 \times 3\text{H}$), 2.243 (s, $0.50 \times 3\text{H}$), 2.38 (s, $0.50 \times 6\text{H}$), 2.42 (s, $0.50 \times 6\text{H}$), 2.84–2.94 (m, 1H), 4.77 (dd, $J = 9.5, 3.0$ Hz, $0.50 \times 1\text{H}$), 4.79–4.84 (m, 1H), 4.92 (ddd, $J = 17.5, 1.5, 1.5$ Hz, $0.50 \times 1\text{H}$), 5.21 (ddd, $J = 10.0, 2.0,$

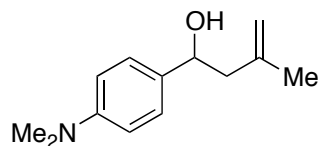
0.5 Hz, $0.50 \times 1\text{H}$), 5.26 (ddd, $J = 17.0, 1.0, 1.0$ Hz, $0.50 \times 1\text{H}$), 5.52 (ddd, $J = 17.0, 10.5, 7.0$ Hz, $0.50 \times 1\text{H}$), 5.89 (ddd, $J = 17.0, 10.0, 8.5$ Hz, $0.50 \times 1\text{H}$), 6.80 (s, $0.50 \times 2\text{H}$), 6.82 (s, $0.50 \times 2\text{H}$); ^{13}C NMR (CDCl_3) δ 16.65, 16.91, 20.90, 21.22, 21.23 (two signals merged), 42.28, 43.99, 74.13, 75.52, 114.40, 116.57, 130.25, 130.37, 134.67, 135.95, 136.54, 136.69, 136.77, 136.98, 140.21, 142.38. HRMS (EI^+) ($\text{M}-\text{H}$) Observed: 203.1441. Calcd for $\text{C}_{14}\text{H}_{19}\text{O}$: 203.1430.

1-(4-Methoxyphenyl)-3-methyl-3-buten-1-ol (3b):



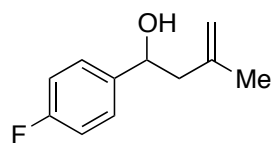
IR (neat) 3415, 2936, 2909, 1612, 1513, 1248, 1175, 1036, 995, 833 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.78–1.80 (m, 3H), 2.08 (d, $J = 2.5$ Hz, 1H), 2.35–2.47 (m, 2H), 3.81 (s, 3H), 4.77 (ddd, $J = 9.0, 4.5, 2.5$ Hz, 1H), 4.84–4.86 (m, 1H), 4.90–4.92 (m, 1H), 6.87–6.90 (m, 2H), 7.29–7.32 (m, 2H); ^{13}C NMR (CDCl_3) δ 22.55, 48.44, 55.46, 71.23, 113.95, 114.15, 127.20, 136.36, 142.69, 159.16. Found: C, 74.75; H, 8.36%. Calcd for $\text{C}_{12}\text{H}_{16}\text{O}_2$: C, 74.97; H, 8.39%.

1-[4-(*N,N*-Dimethylamino)phenyl]-3-Methyl-3-buten-1-ol (3c):



IR (neat) 3382, 2890, 1615, 1522, 1349, 1164, 818 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.78–1.80 (m, 3H), 2.00 (br s, 1H), 2.37–2.41 (m, 1H), 2.47 (ddd, $J = 14.0, 9.5, 1.0$ Hz, 1H), 2.94 (s, 6H), 4.74 (dd, $J = 9.5, 4.5$ Hz, 1H), 4.83–4.85 (m, 1H), 4.88–4.90 (m, 1H), 6.71–6.74 (m, 2H), 7.24–7.27 (m, 2H); ^{13}C NMR (CDCl_3) δ 22.58, 40.85, 48.10, 71.52, 112.70, 113.77, 126.97, 132.13, 143.01, 150.37. Found: C, 75.99; H, 9.32%. Calcd for $\text{C}_{13}\text{H}_{19}\text{NO}$: C, 76.06; H, 9.33%.

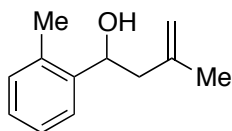
1-(4-Fluorophenyl)-3-methyl-3-buten-1-ol (3d):



IR (neat) 3384, 2938, 2912, 1605, 1510, 1223, 1056, 1015, 980, 838 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.78–1.81 (m, 3H), 2.09 (br s, 1H), 2.37–2.43 (m, 2H), 4.79 (dd, $J = 7.0, 7.0$ Hz, 1H), 4.84–4.86 (m, 1H), 4.92–4.95 (m, 1H), 7.01–7.05 (m, 2H), 7.32–7.37 (m, 2H); ^{13}C NMR (CDCl_3) δ 22.49, 48.67, 70.90, 114.52,

115.37 (d, $J_{\text{C-F}} = 21.5$ Hz), 127.56 (d, $J_{\text{C-F}} = 8.1$ Hz), 139.89 (d, $J_{\text{C-F}} = 3.4$ Hz), 142.32, 162.31 (d, $J_{\text{C-F}} = 243$ Hz). Found: C, 73.41; H, 7.49%. Calcd for $\text{C}_{11}\text{H}_{13}\text{FO}$: C, 73.31; H, 7.27%.

3-Methyl-1-(2-methylphenyl)-3-buten-1-ol (3e):



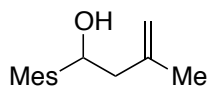
IR (neat) 3368, 2969, 1647, 1457, 1374, 1049, 892, 754, 725 cm^{-1} ; ^1H

NMR (CDCl_3) d 1.83–1.85 (m, 3H), 2.08 (d, $J = 2.5$ Hz, 1H), 2.31–2.41 (m, 2H), 2.35 (s, 3H), 4.89–4.91 (m, 1H), 4.94–4.96 (m, 1H), 5.04 (ddd, $J = 9.5$,

2.5, 2.5 Hz, 1H), 7.12–7.19 (m, 2H), 7.22–7.25 (m, 1H), 7.52–7.54 (m, 1H); ^{13}C NMR (CDCl_3) d 19.14, 22.44, 47.28, 67.95, 114.17, 125.22, 126.50, 127.32, 130.49, 134.29, 142.29, 142.83.

Found: C, 81.78; H, 9.43%. Calcd for $\text{C}_{12}\text{H}_{16}\text{O}$: C, 81.77; H, 9.15%.

1-Mesityl-3-methyl-3-buten-1-ol (3f):

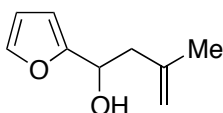


IR (neat) 3566, 2918, 1733, 1521, 1517, 1490, 1044, 890, 751 cm^{-1} ; ^1H

NMR (CDCl_3) d 1.83–1.85 (m, 3H), 1.89 (d, $J = 2.0$ Hz, 1H), 2.25 (s, 3H), 2.29 (dd, $J = 14.0$, 3.5 Hz, 1H), 2.42 (s, 6H), 2.70 (dd, $J = 14.0$, 10.5, 0.5 Hz, 1H), 4.89–4.90 (m, 1H), 4.93–4.95 (m, 1H), 5.24 (ddd, $J = 10.5$, 3.5, 2.0 Hz, 1H), 6.82 (s, 2H); ^{13}C NMR (CDCl_3) d 20.90 (two signals merged), 22.43, 44.35, 69.00, 113.92, 130.33, 136.09, 136.27, 136.68, 143.07.

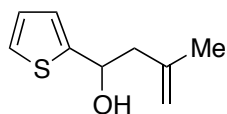
Found: C, 82.43; H, 9.74%. Calcd for $\text{C}_{14}\text{H}_{20}\text{O}$: C, 82.30; H, 9.87%.

1-(2-Furanyl)-3-methyl-3-buten-1-ol (3g):



IR (neat) 3368, 2940, 1647, 1506, 1472, 1375, 1011, 885, 809 cm^{-1} ; ^1H

NMR (CDCl_3) d 1.75–1.78 (m, 3H), 2.13 (d, $J = 4.0$ Hz, 1H), 2.54–2.62 (m, 2H), 4.82–4.87 (m, 1H), 4.84–4.86 (m, 1H), 4.90–4.93 (m, 1H), 6.26 (ddd, $J = 3.0$, 1.0, 1.0 Hz, 1H), 6.33 (dd, $J = 3.0$, 2.0 Hz, 1H), 7.38 (dd, $J = 2.0$, 1.0 Hz, 1H); ^{13}C NMR (CDCl_3) d 22.40, 44.28, 65.47, 106.15, 110.33, 114.35, 141.75, 142.11, 156.23. Found: C, 70.80; H, 7.94%. Calcd for $\text{C}_9\text{H}_{12}\text{O}_2$: C, 71.03; H, 7.95%.

3-Methyl-1-(2-thiophenyl)-3-buten-1-ol (3h):

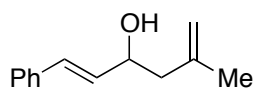
IR (neat) 3366, 2936, 1653, 1647, 1437, 1374, 1042, 893, 706 cm^{-1} ; ^1H

NMR (CDCl_3) δ 1.78–1.81 (m, 3H), 2.27 (d, $J = 3.0$ Hz, 1H), 2.53–2.59 (m, 2H), 4.86–4.88 (m, 1H), 4.92–4.95 (m, 1H), 5.08 (dddd, $J = 9.5, 5.0, 2.5, 1.0$

Hz, 1H), 6.97 (dd, $J = 5.0, 3.5$ Hz, 1H), 6.99 (ddd, $J = 4.0, 1.5, 1.0$ Hz, 1H), 7.24 (dd, $J = 5.0, 1.0$

Hz, 1H); ^{13}C NMR (CDCl_3) δ 22.49, 48.37, 67.76, 114.57, 123.75, 124.64, 126.75, 141.99,

148.06. HRMS (EI^+) (m/z) Observed: 168.0611. Calcd for $\text{C}_9\text{H}_{12}\text{OS}$: 168.0609.

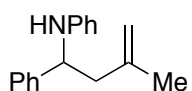
(E)-5-Methyl-1-phenyl-1,5-hexadien-3-ol (3i):

IR (neat) 3360, 2936, 1652, 1647, 1448, 1394, 1071, 966, 892, 748 cm^{-1} ;

^1H NMR (CDCl_3) δ 1.80–1.82 (m, 3H), 1.91 (br s, 1H), 2.30–2.38 (m, 2H), 4.42–4.46 (m, 1H), 4.85–4.88 (m, 1H), 4.92–4.94 (m, 1H), 6.24 (dd, $J = 16.0, 6.5$ Hz, 1H), 6.64 (dd, $J = 16.5, 1.0$ Hz, 1H), 7.22–7.26 (m, 1H), 7.30–7.33 (m, 2H), 7.37–7.40 (m, 2H); ^{13}C NMR

(CDCl_3) δ 22.66, 46.44, 70.07, 114.31, 126.64, 127.79, 128.74, 130.27, 131.87, 136.91, 142.16.

Found: C, 82.69; H, 8.79%. Calcd for $\text{C}_{13}\text{H}_{16}\text{O}$: C, 82.94; H, 8.57%.

3-Methyl-1,N-diphenyl-3-butenylamine (5a):

IR (neat) 3407, 3023, 1602, 1505, 1491, 1314, 1265, 896, 749 cm^{-1} ; ^1H NMR

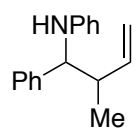
(CDCl_3) δ 1.73–1.76 (m, 3H), 2.40 (dd, $J = 14.5, 10.0$ Hz, 1H), 2.51 (dd, $J = 14.5, 4.5$ Hz, 1H), 4.16 (br s, 1H), 4.38 (dd, $J = 10.0, 4.5$ Hz, 1H), 4.85 (d, $J = 0.5$ Hz, 1H), 4.89–4.92 (m, 1H), 6.48–6.50 (m, 2H), 6.63–6.66 (m, 1H), 7.04–7.09 (m, 2H), 7.21–7.24 (m, 1H), 7.29–7.33 (m, 2H), 7.38–7.40 (m, 2H); ^{13}C NMR (CDCl_3) δ 21.88, 48.27, 55.83, 113.74, 114.29,

117.63, 126.29, 127.12, 128.83, 129.18, 142.63, 144.46, 147.71 Found: C, 85.91; H, 8.11%.

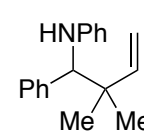
Calcd for $\text{C}_{17}\text{H}_{19}\text{N}$: C, 86.03; H, 8.07%.

2-Methyl-1,N-diphenyl-3-butenylamine (5b):

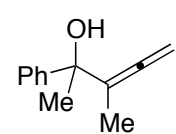
(67:33 mixture of *syn* and *anti* isomers)


 IR (neat) 3414, 2967, 1603, 1505, 1452, 1317, 748 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.99 (d, $J = 7.0$ Hz, $0.67 \times 3\text{H}$) (*syn*), 1.01 (d, $J = 6.5$ Hz, $0.33 \times 3\text{H}$) (*anti*), 2.48–2.55 (m, $0.33 \times 1\text{H}$) (*anti*), 2.64–2.71 (m, $0.67 \times 1\text{H}$) (*syn*), 4.07 (d, $J = 7.0$ Hz, $0.33 \times 1\text{H}$) (*anti*), 4.19 (br s, $0.67 \times 1\text{H}$) (*syn*), 4.22 (br s, $0.33 \times 1\text{H}$) (*anti*), 4.34 (br s, $0.67 \times 1\text{H}$) (*syn*), 5.11–5.21 (m, 2H), 5.70–5.79 (m, 1H), 6.45–6.48 (m, 2H), 6.59–6.62 (m, 1H), 7.02–7.07 (m, 2H), 7.20–7.36 (m, 5H); ^{13}C NMR (CDCl_3) δ 15.43, 17.50, 44.03, 45.44, 61.44, 62.49, 113.46, 113.57, 116.07, 116.44, 117.31, 127.08, 127.17, 127.41, 127.65 (two signals merged), 128.30, 128.52, 129.18, 129.20, 140.50, 140.64, 141.25, 142.82, 147.43, 147.75. Found: C, 85.90; H, 8.19%. Calcd for $\text{C}_{17}\text{H}_{19}\text{N}$: C, 86.03; H, 8.07%.

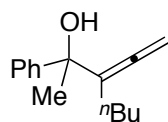
2,2-Dimethyl-1,3-bis(phenyl)but-3-en-1-amine (5c):


 IR (neat) 3415, 2967, 1601, 1504, 1452, 1317, 1258, 919, 748 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.97 (s, 3H), 1.12 (s, 3H), 4.04 (s, 1H), 4.21 (br s, 1H), 5.15 (dd, $J = 16.0$, 1.5 Hz, 1H), 5.18 (dd, $J = 10.5$, 1.5 Hz, 1H), 5.85 (dd, $J = 17.5$, 11.0 Hz, 1H), 6.40–6.43 (m, 2H), 6.56–6.59 (m, 1H), 6.99–7.04 (m, 2H), 7.20–7.24 (m, 1H), 7.25–7.32 (m, 4H); ^{13}C NMR (CDCl_3) δ 23.15, 25.95, 41.49, 66.03, 113.47, 113.97, 117.16, 127.18, 127.92, 128.84, 129.15, 140.50, 145.16, 147.79. Found: C, 85.83; H, 8.35%. Calcd for $\text{C}_{18}\text{H}_{21}\text{N}$: C, 86.01; H, 8.42%.

3-Methyl-2-phenyl-3,4-pentadien-2-ol (6a):

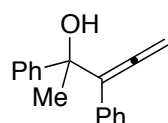

 IR (neat) 3433, 2878, 1867, 1443, 1373, 1173, 1065, 849 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.56 (dd, $J = 3.0$, 3.0 Hz, 3H), 1.66 (s, 3H), 2.05 (s, 1H), 4.84–4.91 (m, 2H), 7.23–7.26 (m, 1H), 7.30–7.36 (m, 2H), 7.45–7.48 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.85, 30.27, 30.32, 75.16, 106.01, 125.42, 127.01, 128.26, 146.12, 205.34. Found: C, 82.48; H, 8.24%. Calcd for $\text{C}_{12}\text{H}_{14}\text{O}$: C, 82.72; H, 8.10%.

3-Butyl-2-phenyl-3,4-pentadien-2-ol (6b):



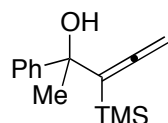
IR (neat) 3448, 2932, 2862, 1952, 1450, 1373, 1173, 1103, 910, 849 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.81 (t, $J = 7.5$ Hz, 3H), 1.19–1.26 (m, 2H), 1.28–1.36 (m, 2H), 1.63–1.70 (m, 1H), 1.66 (s, 3H), 1.82–1.90 (m, 1H), 2.04 (br s, 1H), 4.98 (dt, $J = 3.5, 3.5$ Hz, 2H), 7.22–7.26 (m, 1H), 7.31–7.35 (m, 2H), 7.43–7.46 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.11, 22.55, 26.77, 30.19, 30.60, 75.29, 79.55, 115.58, 125.47, 126.97, 128.23, 146.46, 204.75. HRMS (EI^+) ($\text{M}-\text{H}$) Observed: 215.1426. Calcd for $\text{C}_{15}\text{H}_{19}\text{O}$: 215.1430.

2,3-Diphenyl-3,4-pentadien-2-ol (6c):



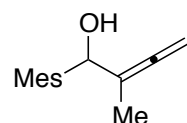
IR (nujol) 3340, 2862, 1936, 1458, 1373, 1196, 1065 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.73 (s, 3H), 2.25 (s, 1H), 5.23 (d, $J = 2.5$ Hz, 2H), 7.11–7.18 (m, 5H), 7.23–7.26 (m, 1H), 7.31–7.35 (m, 2H), 7.54–7.56 (m, 2H); ^{13}C NMR (CDCl_3) δ 32.85, 32.91, 75.43, 79.21, 112.65, 125.39, 127.10, 128.40, 128.46, 128.58, 134.37, 147.15, 208.18. Found: C, 86.49; H, 6.80%. Calcd for $\text{C}_{17}\text{H}_{16}\text{O}$: C, 86.40; H, 6.82%. m.p.: 62–65 $^{\circ}\text{C}$.

2-Phenyl-3-trimethylsilyl-3,4-pentadien-2-ol (6d):

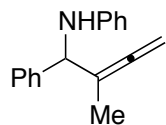


IR (neat) 3440, 2962, 1921, 1450, 1327, 1250, 1065, 841 cm^{-1} ; ^1H NMR (CDCl_3) δ -0.04 (s, 9H), 1.71 (s, 3H), 1.99 (s, 1H), 4.60 (d, $J = 1.5$ Hz, 2H), 7.21–7.24 (m, 1H), 7.30–7.33 (m, 2H), 7.46–7.48 (m, 2H); ^{13}C NMR (CDCl_3) δ 0.12, 32.72, 71.84, 76.14, 105.43, 125.44, 126.84, 128.04, 147.76, 208.31. Found: C, 72.36; H, 8.80%. Calcd for $\text{C}_{14}\text{H}_{20}\text{OSi}$: C, 72.36; H, 8.67%.

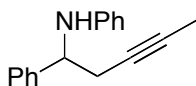
1-Mesityl-2-methyl-2,3-butadien-1-ol (6e):



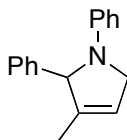
IR (neat) 3418, 2916, 2862, 1960, 1612, 1443, 1049, 849 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.55 (ddd, $J = 3.0, 3.0, 1.0$ Hz, 3H), 2.13 (d, $J = 4.0$ Hz, 1H), 2.25 (s, 3H), 2.37 (s, 6H), 4.89–4.92 (m, 2H), 5.55–5.57 (m, 1H), 6.81 (s, 2H); ^{13}C NMR (CDCl_3) δ 15.84, 20.51, 20.97, 69.61, 78.96, 102.63, 130.17, 133.59, 137.17, 137.42, 203.98. Found: C, 83.14; H, 9.12%. Calcd for $\text{C}_{14}\text{H}_{18}\text{O}$: C, 83.12; H, 8.97%.

2-Methyl-1,*N*-diphenyl-2,3-butadienylamine (7aa)

IR (neat) 3450, 3060, 1921, 1605, 1504, 1427, 1319, 1265, 856 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.64 (dd, $J = 3.0, 2.5$ Hz, 3H), 4.29 (br d, $J = 5.0$ Hz, 1H), 4.73–4.75 (m, 1H), 4.80–4.88 (m, 2H), 6.57–6.60 (m, 2H), 6.66–6.69 (m, 1H), 7.10–7.14 (m, 2H), 7.24–7.28 (m, 1H), 7.32–7.35 (m, 2H), 7.39–7.42 (m, 2H); ^{13}C NMR (CDCl_3) δ 16.16, 60.69, 77.72, 101.21, 113.70, 117.69, 127.41, 127.68, 128.74, 129.24, 141.74, 147.30, 205.76. Found: C, 86.53; H, 7.05%. Calcd for $\text{C}_{17}\text{H}_{17}\text{N}$: C, 86.77; H, 7.28%.

1,*N*-Diphenyl-3-pentynylamine (8aa)

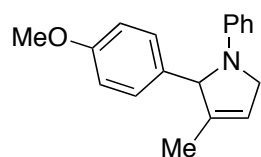
IR (neat) 3402, 3024, 2916, 2854, 1605, 1504, 1427, 1312, 1273 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.78 (dd, $J = 2.5, 2.5$ Hz, 3H), 2.52–2.60 (m, 1H), 2.65–2.73 (m, 1H), 4.41–4.47 (m, 2H), 6.52–6.55 (m, 2H), 6.64–6.68 (m, 1H), 7.07–7.11 (m, 2H), 7.22–7.25 (m, 1H), 7.29–7.33 (m, 2H), 7.37–7.39 (m, 2H); ^{13}C NMR (CDCl_3) δ 3.73, 28.90, 57.21, 75.23, 78.96, 113.90, 117.77, 126.50, 127.45, 128.74, 129.24, 142.93, 147.53. Found: C, 86.86; H, 7.38%. Calcd for $\text{C}_{17}\text{H}_{17}\text{N}$: C, 86.77; H, 7.28%.

3-Methyl-1,2-diphenyl-3-pyrroline (9aa):

IR (nujol) 2924, 2854, 1458, 1373, 748 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.56–1.57 (m, 3H), 4.15–4.20 (m, 1H), 4.41–4.47 (m, 1H), 5.09–5.10 (m, 1H), 5.60 (ddd, $J = 5.0, 3.0, 1.5$ Hz, 1H), 6.47–6.50 (m, 2H), 6.58–6.62 (m, 1H), 7.09–7.14 (m, 2H), 7.20–7.24 (m, 1H), 7.27–7.32 (m, 4H); ^{13}C

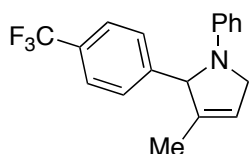
NMR (CDCl₃) δ 14.08, 55.80, 72.83, 112.05, 115.95, 119.09, 126.90, 127.42, 128.81, 129.20, 140.46, 142.63, 146.64. Found: C, 86.74; H, 7.29%. Calcd for C₁₇H₁₇N: C, 86.77; H, 7.28%. m.p.: 92–94 °C.

2-(4-Methoxyphenyl)-3-methyl-1-phenyl-3-pyrroline (9ab):



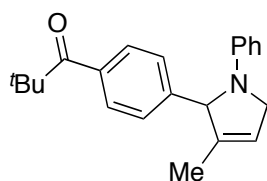
IR (nujol) 2947, 2831, 1674, 1605, 1504, 1474, 1366, 1242, 1173, 1034 cm⁻¹; ¹H NMR (CDCl₃) δ 1.55–1.57 (m, 3H), 3.77 (s, 3H), 4.12–4.17 (m, 1H), 4.39–4.45 (m, 1H), 5.04–5.08 (m, 1H), 5.57–5.59 (m, 1H), 6.48–6.51 (m, 2H), 6.58–6.62 (m, 1H), 6.82–6.85 (m, 2H), 7.10–7.14 (m, 2H), 7.18–7.21 (m, 2H); ¹³C NMR (CDCl₃) δ 14.04, 55.40, 55.71, 72.22, 112.07, 114.23, 115.89, 118.80, 127.97, 129.17, 134.66, 140.70, 146.73, 158.99. Found: C, 81.30; H, 7.16%. Calcd for C₁₈H₁₉NO: C, 81.47; H, 7.22%. m.p.: 64–66 °C.

3-Methyl-1-phenyl-2-(4-trifluoromethylphenyl)-3-pyrroline (9ac):



IR (nujol) 3063, 2824, 1605, 1504, 1366, 1327, 1165 cm⁻¹; ¹H NMR (CDCl₃) δ 1.56–1.58 (m, 3H), 4.17–4.22 (m, 1H), 4.43–4.48 (m, 1H), 5.14–5.18 (m, 1H), 5.64 (ddd, *J* = 5.5, 3.5, 2.0 Hz, 1H), 6.44–6.46 (m, 2H), 6.62–6.66 (m, 1H), 7.11–7.15 (m, 2H), 7.39–7.43 (m, 2H), 7.55–7.58 (m, 2H); ¹³C NMR (CDCl₃) δ 13.92, 55.86, 72.41, 112.11, 116.48, 119.96, 124.40 (q, *J*_{C-F} = 270.5 Hz), 125.85 (q, *J*_{C-F} = 3.8 Hz), 127.25, 129.32, 129.75 (q, *J*_{C-F} = 32.3 Hz), 139.61, 146.33, 146.94. Found: C, 71.23; H, 5.44%. Calcd for C₁₈H₁₆F₃N: C, 71.28; H, 5.32%. m.p.: 74–76 °C.

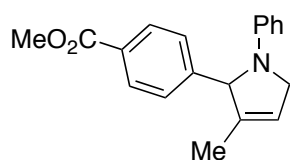
3-Methyl-1-phenyl-2-(4-pivaloylphenyl)-3-pyrroline (9ad):



IR (nujol) 3040, 1666, 1597, 1404, 1366, 1273, 1188 cm⁻¹; ¹H NMR (CDCl₃) δ 1.33 (s, 9H), 1.56–1.58 (m, 3H), 4.16–4.22 (m, 1H), 4.42–4.48 (m, 1H), 5.12–5.16 (m, 1H), 5.63 (ddd, *J* = 3.5, 3.5, 2.0 Hz, 1H), 6.45–6.49 (m, 2H), 6.61–6.65 (m, 1H), 7.11–7.16 (m, 2H), 7.31–7.34 (m,

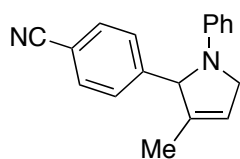
2H), 7.68–7.71 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.07, 28.29, 44.31, 55.86, 72.52, 112.08, 116.27, 119.70, 126.58, 128.83, 129.28, 137.53, 139.84, 145.93, 146.45, 208.74. Found: C, 82.82; H, 7.73%. Calcd for $\text{C}_{22}\text{H}_{25}\text{NO}$: C, 82.72; H, 7.89%. m.p.: 112–115 °C.

2-(4-Methoxycarbonylphenyl)-3-methyl-1-phenyl-3-pyrroline (9ae):



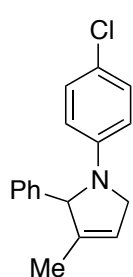
IR (nujol) 2923, 2854, 1720, 1597, 1458, 1373, 1273, 1103 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.55–1.57 (m, 3H), 3.89 (s, 3H), 4.17–4.22 (m, 1H), 4.43–4.48 (m, 1H), 5.14–5.18 (m, 1H), 5.63–5.66 (m, 1H), 6.44–6.47 (m, 2H), 6.60–6.64 (m, 1H), 7.10–7.14 (m, 2H), 7.35–7.38 (m, 2H), 7.98–8.00 (m, 2H); ^{13}C NMR (CDCl_3) δ 13.99, 52.18, 55.84, 72.63, 112.08, 116.35, 119.88, 126.95, 129.27, 129.52, 130.27, 139.69, 146.38, 148.16, 167.12. Found: C, 77.92; H, 6.49%. Calcd for $\text{C}_{19}\text{H}_{19}\text{NO}_2$: C, 77.79; H, 6.53%. m.p.: 105–108 °C.

2-(4-Cyanophenyl)-3-methyl-1-phenyl-3-pyrroline (9af):



Red amorphous solid; IR (nujol) 3063, 2978, 2831, 2230, 1605, 1366, 1219, 1026 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.55–1.57 (m, 3H), 4.16–4.22 (m, 1H), 4.42–4.48 (m, 1H), 5.13–5.17 (m, 1H), 5.64–5.68 (m, 1H), 6.40–6.44 (m, 2H), 6.63–6.67 (m, 1H), 7.10–7.16 (m, 2H), 7.38–7.42 (m, 2H), 7.59–7.62 (m, 2H); ^{13}C NMR (CDCl_3) δ 13.97, 55.88, 72.49, 111.40, 112.07, 116.68, 119.00, 120.42, 127.67, 129.36, 132.78, 139.14, 146.10, 148.43. HRMS (EI^+) (m/z) Observed: 260.1313. Calcd for $\text{C}_{18}\text{H}_{16}\text{N}_2$: 260.1313.

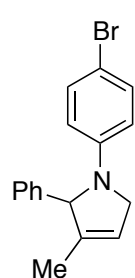
1-(4-Chlorophenyl)-3-methyl-2-phenyl-3-pyrroline (9ag):



IR (nujol) 2854, 1458, 1373, 1308 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.55–1.58 (m, 3H), 4.11–4.17 (m, 1H), 4.37–4.44 (m, 1H), 5.04–5.08 (m, 1H), 5.58–5.61 (m, 1H), 6.36–6.40 (m, 2H), 7.02–7.06 (m, 2H), 7.23–7.26 (m, 3H), 7.29–7.32 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.04, 55.88, 72.89, 113.07, 118.96, 120.83, 126.84, 127.63, 128.91,

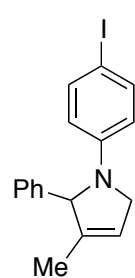
128.98, 140.52, 142.09, 145.10. Found: C, 75.85; H, 5.89%. Calcd for $C_{17}H_{16}ClN$: C, 75.69; H, 5.98%. m.p.: 128–132 °C.

1-(4-Bromophenyl)-3-methyl-2-phenyl-3-pyrroline (9ah):



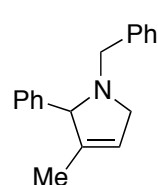
IR (nujol) 2924, 2854, 1589, 1458, 1373 cm^{-1} ; 1H NMR ($CDCl_3$) δ 1.55–1.57 (m, 3H), 4.10–4.16 (m, 1H), 4.36–4.43 (m, 1H), 5.03–5.07 (m, 1H), 5.59 (ddd, $J = 5.0, 3.5, 1.5$ Hz, 1H), 6.32–6.36 (m, 2H), 7.15–7.33 (m, 7H); ^{13}C NMR ($CDCl_3$) δ 14.02, 55.82, 72.84, 107.96, 113.66, 118.92, 126.83, 127.65, 128.91, 131.83, 140.52, 142.00, 145.46. Found: C, 64.97; H, 5.11%. Calcd for $C_{17}H_{16}BrN$: C, 64.98; H, 5.13%. m.p.: 138–142 °C.

1-(4-Iodophenyl)-3-methyl-2-phenyl-3-pyrroline (9ai):

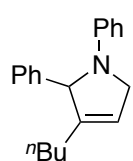


IR (nujol) 2924, 2854, 1582, 1458, 1373 cm^{-1} ; 1H NMR ($CDCl_3$) δ 1.55–1.57 (m, 3H), 4.09–4.15 (m, 1H), 4.36–4.42 (m, 1H), 5.03–5.07 (m, 1H), 5.57–5.60 (m, 1H), 6.23–6.27 (m, 2H), 7.21–7.25 (m, 3H), 7.29–7.35 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 14.02, 55.71, 72.74, 76.90, 114.45, 118.87, 126.82, 127.65, 128.91, 137.67, 140.49, 141.93, 145.97. Found: C, 56.73; H, 4.50%. Calcd for $C_{17}H_{16}IN$: C, 56.53; H, 4.46%. m.p.: 64–68 °C.

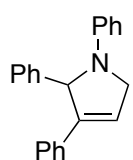
1-Benzyl-3-methyl-2-phenyl-3-pyrroline (9aj):



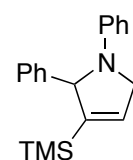
IR (neat) 3072, 3028, 2878, 2786, 1490, 1451 cm^{-1} ; 1H NMR ($CDCl_3$) δ 1.43–1.46 (m, 3H), 3.20–3.27 (m, 1H), 3.52 (d, $J = 13.0$ Hz, 1H), 3.64–3.70 (m, 1H), 3.89 (d, $J = 13.0$ Hz, 1H), 4.34–4.38 (m, 1H), 5.47–5.51 (m, 1H), 7.16–7.22 (m, 1H), 7.23–7.28 (m, 5H), 7.31–7.36 (m, 2H), 7.38–7.41 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 14.44, 57.76, 58.43, 77.38, 121.66, 126.82, 127.38, 128.27, 128.33, 128.61, 128.73, 140.09, 140.62, 142.60. HRMS (EI^+) (m/z) Observed: 249.1512. Calcd for $C_{18}H_{19}N$: 249.1517.

3-Butyl-1,2-diphenyl-3-pyrroline (9ba)

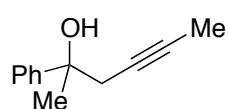
IR (neat) 2932, 2862, 1597, 1504, 1473, 1366, 748 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.85 (t, $J = 7.5$ Hz, 3H), 1.20–1.50 (m, 4H), 1.76–1.88 (m, 2H), 4.16–4.21 (m, 1H), 4.41–4.47 (m, 1H), 5.14–5.18 (m, 1H), 5.58–5.60 (m, 1H), 6.47–6.51 (m, 2H), 6.57–6.61 (m, 1H), 7.09–7.13 (m, 2H), 7.19–7.23 (m, 1H), 7.26–7.31 (m, 4H); ^{13}C NMR (CDCl_3) δ 14.05, 22.54, 27.73, 29.56, 55.81, 71.83, 112.02, 115.92, 117.80, 127.00, 127.39, 128.78, 129.18, 142.92, 145.16, 146.65. Found: C, 86.48; H, 8.44%. Calcd for $\text{C}_{20}\text{H}_{23}\text{N}$: C, 86.59; H, 8.36%.

1,2,3-Triphenyl-3-pyrroline (9ca):

IR (nujol) 2924, 2854, 1597, 1458, 1373, 1172 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.39 (ddd, $J = 14.5, 2.5, 2.5$ Hz, 1H), 4.60 (ddd, $J = 15.0, 6.0, 2.0$ Hz, 1H), 5.80 (ddd, $J = 6.0, 2.0, 2.0$ Hz, 1H), 6.25 (ddd, $J = 2.0, 2.0, 2.0$ Hz, 1H), 6.59–6.66 (m, 3H), 7.07–7.12 (m, 1H), 7.13–7.25 (m, 7H), 7.30–7.37 (m, 4H); ^{13}C NMR (CDCl_3) δ 56.06, 70.10, 111.93, 116.19, 121.16, 126.89, 127.44, 127.84, 127.88, 128.44, 128.58, 129.27, 134.21, 142.21, 144.37, 146.21. Found: C, 89.12; H, 6.44%. Calcd for $\text{C}_{22}\text{H}_{19}\text{N}$: C, 88.85; H, 6.44%. m.p.: 135–137 $^{\circ}\text{C}$.

3-Trimethylsilyl-1,2-diphenyl-3-pyrroline (9da):

IR (nujol) 2924, 2854, 1597, 1504, 1458, 1373, 1250, 1180 cm^{-1} ; ^1H NMR (CDCl_3) δ -0.13 (s, 9H), 4.27 (ddd, $J = 14.5, 3.0, 2.0$ Hz, 1H), 4.53 (ddd, $J = 14.5, 6.0, 2.0$ Hz, 1H), 5.44 (ddd, $J = 6.0, 3.0, 2.0$ Hz, 1H), 6.19–6.21 (m, 1H), 6.55–6.58 (m, 2H), 6.60–6.64 (m, 1H), 7.11–7.16 (m, 2H), 7.19–7.23 (m, 1H), 7.27–7.33 (m, 4H); ^{13}C NMR (CDCl_3) δ -1.55, 57.85, 73.92, 112.21, 115.95, 127.46, 127.55, 128.75, 129.20, 134.21, 143.79, 146.49, 146.70. HRMS (EI^+) (m/z) Observed: 293.1603. Calcd for $\text{C}_{19}\text{H}_{23}\text{NSi}$: 293.1600. m.p.: 88–90 $^{\circ}\text{C}$.

2-Phenyl-4-hexyn-2-ol (10)

IR (neat) 3448, 2978, 2916, 1497, 1443, 1373, 1273, 1095, 949 cm^{-1} ; ^1H

NMR (CDCl_3) d 1.60 (s, 3H), 1.78 (dd, $J = 2.5, 2.5$ Hz, 3H), 2.63 (dq, $J =$

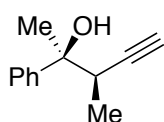
16.5, 2.5 Hz, 1H), 2.70 (dq, $J = 16.5, 2.5$ Hz, 1H), 7.24–7.27 (m, 1H), 7.33–7.37 (m, 2H),

7.46–7.49 (m, 2H); ^{13}C NMR (CDCl_3) d 3.72, 29.42, 35.20, 73.42, 75.02, 79.63, 124.90, 127.07,

128.33, 146.99. Found: C, 82.99; H, 8.30%. Calcd for $\text{C}_{12}\text{H}_{14}\text{O}$: C, 82.72; H, 8.10%.

3-Methyl-2-phenyl-4-pentyn-2-ol (11a)

(*syn* isomer)



IR (neat) 3487, 3294, 2986, 2939, 1450, 1373, 1173, 1073, 926 cm^{-1} ; ^1H NMR

(CDCl_3) d 0.97 (d, $J = 7.0$ Hz, 3H), 1.70 (s, 3H), 2.12 (s, 1H), 2.21 (d, $J = 2.5$ Hz,

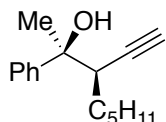
1H), 2.86 (dq, $J = 2.5, 7.0$ Hz, 1H), 7.23–7.26 (m, 1H), 7.32–7.36 (m, 2H),

7.41–7.44 (m, 2H); ^{13}C NMR (CDCl_3) d 15.85, 29.72, 38.73, 71.66, 75.17, 85.94, 125.22,

126.92, 128.23, 145.04. Found: C, 82.45; H, 8.12%. Calcd for $\text{C}_{12}\text{H}_{14}\text{O}$: C, 82.72; H, 8.10%.

3-Pentyl-2-phenyl-4-pentyn-2-ol (11b)

(*syn* isomer)



IR (neat) 3487, 3302, 2932, 2862, 1450, 1373, 1180, 1065 cm^{-1} ; ^1H NMR

(CDCl_3) d 0.82 (t, $J = 7.5$ Hz, 3H), 1.08–1.27 (m, 6H), 1.32–1.40 (m, 1H),

1.47–1.56 (m, 1H), 1.69 (s, 3H), 2.16 (s, 1H), 2.22 (d, $J = 2.5$ Hz, 1H), 2.72 (ddd,

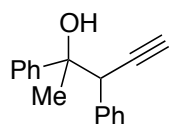
$J = 11.0, 3.0, 2.5$ Hz, 1H), 7.23–7.26 (m, 1H), 7.32–7.36 (m, 2H), 7.40–7.43 (m, 2H); ^{13}C NMR

(CDCl_3) d 14.18, 22.68, 27.66, 29.35, 30.04, 31.58, 44.95, 72.62, 75.44, 84.86, 125.17, 126.87,

128.25, 145.42. Found: C, 83.64; H, 9.86%. Calcd for $\text{C}_{16}\text{H}_{22}\text{O}$: C, 83.43; H, 9.63%.

2,3-Diphenyl-4-pentyn-2-ol (11c)

(53:47 mixture of two diastereomers)



IR (neat) 3556, 3472, 3294, 3032, 2978, 1605, 1497, 1450, 1288, 1072 cm^{-1} ; ^1H

NMR (CDCl_3) δ 1.54 (s, $0.47 \times 3\text{H}$), 1.77 (s, $0.53 \times 3\text{H}$), 2.19–2.20 (m, $0.53 \times$

1H), 2.30–2.33 (m, $0.47 \times 1\text{H}$), 2.34–2.36 (m, $0.53 \times 1\text{H}$), 2.51–2.53 (m, $0.47 \times$

1H), 3.99–4.01 (m, $0.53 \times 1\text{H}$), 4.05–4.07 (m, $0.47 \times 1\text{H}$), 7.07–7.15 (m, 2H), 7.17–7.34 (m, 8H);

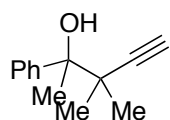
^{13}C NMR (CDCl_3) δ 26.23, 27.41, 51.36, 51.69, 73.43 (two signals merged), 76.10, 76.44, 83.60,

83.71, 125.81, 125.91, 127.15, 127.35, 127.50, 127.58, 127.84, 127.95 (two signals merged),

127.99, 129.78, 129.83, 136.68, 136.72, 144.81, 145.09. Found: C, 86.59; H, 6.97%. Calcd

for $\text{C}_{17}\text{H}_{16}\text{O}$: C, 86.40; H, 6.82%.

3,3-Dimethyl-2-phenyl-4-pentyn-2-ol (11d)



IR (neat) 3556, 3294, 2986, 2939, 1450, 1373, 1173, 1111, 910 cm^{-1} ; ^1H NMR

(CDCl_3) δ 1.15 (s, 3H), 1.19 (s, 3H), 1.76 (s, 3H), 2.25 (s, 1H), 2.26 (s, 1H),

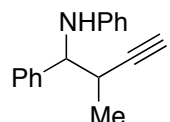
7.24–7.27 (m, 1H), 7.30–7.34 (m, 2H), 7.51–7.54 (m, 2H); ^{13}C NMR (CDCl_3) δ

25.09, 25.33, 26.06, 41.42, 70.85, 77.22, 90.28, 127.08, 127.27, 127.43, 143.27. Found: C,

82.87; H, 8.74%. Calcd for $\text{C}_{13}\text{H}_{16}\text{O}$: C, 82.94; H, 8.57%.

2-Methyl-1,N-diphenyl-3-butyneamine (12aa)

(77:23 mixture of two diastereomers)



IR (neat) 3410, 3286, 3024, 2978, 1605, 1504, 1450, 1312, 1281, 1072 cm^{-1} ; ^1H

NMR (CDCl_3) δ 1.11 (d, $J = 7.5$ Hz, $0.23 \times 3\text{H}$), 1.30 (d, $J = 7.5$ Hz, $0.77 \times 3\text{H}$),

2.171 (d, $J = 2.5$ Hz, $0.23 \times 1\text{H}$), 2.175 (d, $J = 2.5$ Hz, $0.77 \times 1\text{H}$), 2.84–2.90 (m,

$0.77 \times 1\text{H}$), 3.04–3.10 (m, $0.23 \times 1\text{H}$), 4.27 (dd, $J = 5.5, 5.5$ Hz, $0.77 \times 1\text{H}$), 4.39 (dd, $J = 5.5, 5.5$

Hz, $0.23 \times 1\text{H}$), 4.48 (br d, $J = 6.0$ Hz, $0.23 \times 1\text{H}$), 4.58 (br d, $J = 5.5$ Hz, $0.77 \times 1\text{H}$), 6.52–6.55

(m, 2H), 6.62–6.66 (m, 1H), 7.05–7.09 (m, 2H), 7.22–7.26 (m, 1H), 7.29–7.32 (m, 2H),

7.36–7.39 (m, 2H); ^{13}C NMR (CDCl_3) δ 17.28, 19.32, 32.76, 34.62, 60.86, 61.71, 71.84, 72.03,

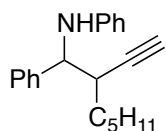
84.90, 85.28, 113.68, 113.89, 117.64, 117.80, 127.07, 127.57, 127.65, 127.83, 128.34, 128.60,

129.26, 129.28, 139.93, 142.07, 147.22, 147.54. Found: C, 87.03; H, 7.32%. Calcd for

$C_{17}H_{17}N$: C, 86.77; H, 7.28%.

2-Pentyl-1,*N*-diphenyl-3-butyneamine (12ba)

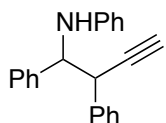
(82:18 mixture of two diastereomers)



IR (neat) 3410, 3294, 2932, 2862, 1605, 1504, 1312, 1273, 748 cm^{-1} ; 1H NMR ($CDCl_3$) δ 0.85–0.91 (m, 3H), 1.17–1.71 (m, 8H), 2.18 (d, $J = 2.5$ Hz, 1H), 2.72–2.77 (m, $0.82 \times 1H$), 2.93–2.97 (m, $0.18 \times 1H$), 4.37 (dd, $J = 6.0, 5.0$ Hz, $0.82 \times 1H$), 4.43 (dd, $J = 6.0, 5.0$ Hz, $0.18 \times 1H$), 4.53 (d, $J = 6.5$ Hz, $0.18 \times 1H$), 4.60 (d, $J = 6.5$ Hz, $0.82 \times 1H$), 6.51–6.54 (m, 2H), 6.61–6.65 (m, 1H), 7.06–7.10 (m, 2H), 7.21–7.26 (m, 1H), 7.29–7.32 (m, 2H), 7.36–7.40 (m, 2H); ^{13}C NMR ($CDCl_3$) for the major isomer δ 14.20, 22.70, 27.37, 31.65, 33.19, 40.84, 59.96, 72.98, 83.75, 113.57, 117.50, 127.00, 127.45, 128.58, 129.30, 142.34, 147.46. Found: C, 86.60; H, 8.73%. Calcd for $C_{21}H_{25}N$: C, 86.55; H, 8.65%.

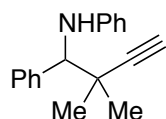
1,2,*N*-Triphenyl-3-butyneamine (12ca)

(55:45 mixture of two diastereomers)



IR (neat) 3410, 3286, 3032, 2885, 1605, 1504, 1450, 1312, 1265 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.35 (dd, $J = 2.5, 0.5$ Hz, $0.45 \times 1H$), 2.39 (dd, $J = 2.5, 0.5$ Hz, $0.55 \times 1H$), 4.06 (dd, $J = 5.0, 2.0$ Hz, $0.55 \times 1H$), 4.29 (dd, $J = 4.8, 2.3$ Hz, $0.45 \times 1H$), 4.40–4.74 (br m, 1H), 4.59 (d, $J = 5.0$ Hz, $0.55 \times 1H$), 4.66 (d, $J = 5.5$ Hz, $0.45 \times 1H$), 6.44–6.49 (m, $0.55 \times 2H$), 6.49–6.53 (m, $0.45 \times 2H$), 6.58–6.66 (m, 1H), 7.00–7.12 (m, 4H), 7.13–7.30 (m, 8H); ^{13}C NMR ($CDCl_3$) δ 45.15, 46.07, 62.35, 62.83, 74.28, 74.55, 82.21, 82.43, 113.90, 113.99, 117.81, 117.98, 127.28, 127.62, 127.67, 127.88, 128.00, 128.42, 128.44, 128.47, 128.55, 128.76, 128.94, 128.97, 129.21, 129.28, 137.01, 137.98, 139.07, 141.07, 146.79, 147.12. HRMS (EI^+) (m/z) Observed: 297.1514. Calcd for $C_{22}H_{19}N$: 297.1517.

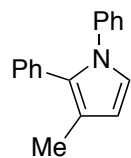
2,2-Dimethyl-1,*N*-diphenyl-3-butyneamine (12da)



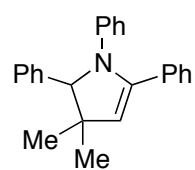
IR (neat) 3410, 3286, 2978, 2932, 1605, 1504, 1312, 1258, 1180 cm^{-1} ; 1H NMR

(CDCl₃) d 1.09 (s, 3H), 1.46 (s, 3H), 2.30 (s, 1H), 4.08 (s, 1H), 4.70 (s, 1H), 6.51–6.54 (m, 2H), 6.58–6.62 (m, 1H), 7.03–7.08 (m, 2H), 7.21–7.30 (m, 3H), 7.40–7.42 (m, 2H); ¹³C NMR (CDCl₃) d 26.95, 29.14, 37.02, 65.64, 71.71, 88.58, 113.63, 117.41, 127.63, 128.05, 128.50, 129.23, 140.21, 147.51. Found: C, 86.68; H, 7.76%. Calcd for C₁₈H₁₉N: C, 86.70; H, 7.68%.

3-Methyl-1,2-diphenylpyrrole (13):

 IR (neat) 3047, 2924, 1596, 1497, 1350, 1219, 1072, 764 cm⁻¹; ¹H NMR (CDCl₃) d 2.19 (s, 3H), 6.24–6.26 (m, 1H), 6.88 (d, *J* = 2.5 Hz, 1H), 7.05–7.10 (m, 4H), 7.15–7.19 (m, 2H), 7.22–7.26 (m, 4H); ¹³C NMR (CDCl₃) d 12.36, 111.25, 119.14, 122.42, 125.52, 126.13, 126.42, 128.06, 128.97, 130.27, 130.38, 132.81, 140.88. Found: C, 87.40; H, 6.64%. Calcd for C₁₇H₁₅N: C, 87.52; H, 6.48%.

4,4-Dimethyl-1,2,5-triphenyl-2-pyrroline (14)

 Yellow amorphous solid; IR (nujol) 2854, 1597, 1458, 1373, 1296 cm⁻¹; ¹H NMR (CDCl₃) d 0.70 (s, 3H), 1.32 (s, 3H), 4.55 (s, 1H), 5.21 (s, 1H), 6.57–6.60 (m, 2H), 6.73–6.78 (m, 1H), 6.97–7.02 (m, 2H), 7.22–7.30 (m, 4H), 7.32–7.40 (m, 4H), 7.46–7.48 (m, 2H); ¹³C NMR (CDCl₃) d 24.59, 32.36, 46.79, 82.80, 118.76, 120.24, 120.81, 126.89, 127.28, 127.32, 127.93, 128.42, 128.50 (two signals merged), 133.74, 142.03, 145.27, 148.17. HRMS (EI⁺) (*m/z*) Observed: 325.1838. Calcd for C₂₄H₂₃N: 325.1830.

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Chapter 2

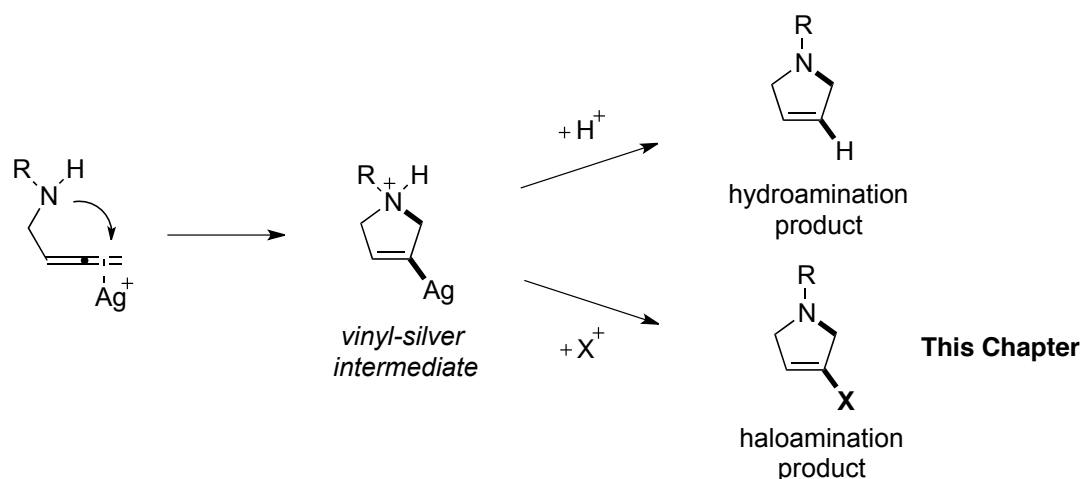
Silver-Catalyzed Intramolecular Chloroamination of Allenes: Easy Access to Functionalized 3-Pyrroline and Pyrrole Derivatives

A 1,10-phenanthroline-ligated cationic silver complex allows the intramolecular chloroamination of allenes with *N*-chlorosuccinimide using 2,6-lutidine as a base. This process proceeds under mild conditions and can tolerate a variety of functional groups. The chloroamination products are useful synthetic intermediates and can be easily transformed into functionalized 3-pyrroline and pyrrole derivatives.

Introduction

The intramolecular haloamination of alkenes has emerged as a powerful tool for the construction of azacycles carrying halogen atoms at the β -position of the nitrogen.¹ These reactions have been performed using a halogen cation equivalent (X^+) with/without transition-metal catalysts.^{2,3} However, reactions with alkynes^{3d} or allenes⁴ instead of alkenes have hardly been investigated thus far. In Chapter 1, the author reported a new method for the easy preparation of α -aminoallenes. When the intramolecular haloamination of α -aminoallene proceeds in a 5-*endo* manner, it yields a pyrroline derivative with a halogen on sp^2 -carbon. The alkenyl halide moiety can be utilized for further transformations such as cross-coupling reactions. Furthermore, pyrrolines are readily converted to synthetically useful pyrrole derivatives. In this manner, the intramolecular haloamination of allenes are extremely important. To realize the proposed reaction, the author initially focused on silver catalysts since they have already been demonstrated to be effective in activating C–C multiple bonds toward the addition of various functional groups.⁵ In particular, the silver-catalyzed 5-*endo-trig* cyclization of α -aminoallenes has been well established.^{5,6} In this transformation, as outlined in Scheme 1, the vinyl-silver intermediate is considered to be generated by the intramolecular addition of the amine to the activated π -bond. Subsequently, the resulting $C(sp^2)$ –Ag bond is rapidly quenched by a proton to afford the intramolecular hydroamination product. However, this mechanism suggests that the intermediate can be trapped by an electrophile other than a proton.^{7,8} Therefore, if a halogen cation equivalent (X^+) can intercept the intermediate prior to protonation, a facile and efficient method for the synthesis of 3-pyrrolines bearing a $C(sp^2)$ –X bond can be achieved. In Chapter 2, the author reports that a 1,10-phenanthroline-ligated cationic silver complex allows the intramolecular chloroamination of allenes with *N*-chlorosuccinimide (NCS) using 2,6-lutidine as a base.

Scheme 1.

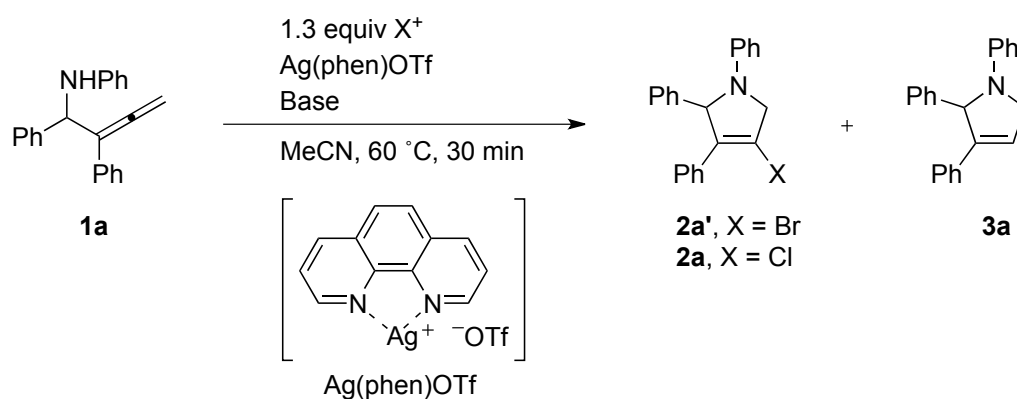


Results and Discussion

Initial investigations were performed using *N*-bromosuccinimide (NBS) as an electrophilic halogen source. To our delight, treatment of α -aminoallene **1a** with NBS in the presence of a catalytic amount of $\text{Ag}(\text{phen})\text{OTf}$ ⁹ did provide the desired bromoamination product **2a**. However, a substantial amount of the hydroamination byproduct **3a** was also formed (Table 1, entries 1 and 2). Our attempts to improve the reaction by increasing the amount of the catalyst or NBS were unsuccessful (Table 1, entries 3 and 4). Hence, to suppress the undesired formation of **3a**, we replaced NBS with *N*-chlorosuccinimide (NCS). The use of NCS efficiently suppressed the competitive side reaction, and the chloroamination product **2a** was obtained in a fairly good yield (Table 1, entry 5).¹⁰

We further hypothesized that an appropriate base could temper the reaction acidity and retard the protonation of the presumed vinyl-silver intermediate. Therefore, our next step was to test the effects of base additives. Consequently, we found that the reaction outcomes were closely related to the $\text{p}K_{\text{b}}$ values of the employed bases.¹¹ The addition of strong bases such as DBU, triethylamine ($\text{p}K_{\text{b}} = 9.00$), and *N*-methylimidazole seriously inhibited the cyclization step probably due to the coordination to the metal center (Table 1, entries 6–8). The use of weak

bases such as pyridine ($pK_b = 3.4$) and 2,6-di-*tert*-butylpyridine ($pK_b = 0.90$) did not have beneficial effects on this reaction (Table 1, entries 9 and 10). We eventually found that the addition of a mild base 2,6-lutidine ($pK_b = 4.46$) significantly prevented the formation of **3a**, leading to the improved yield of **2a** (Table 1, entry 11). Inorganic bases gave poor results (Table 1, entries 12 and 13). It should be noted that **2a** was not formed in the absence of silver catalysts. Further optimization of the reaction conditions revealed that the catalyst and base amounts could be reduced without any loss in the yield of **2a** (Table 1, entry 14). The product **2a** underwent partial decomposition during silica gel column chromatography even under basic conditions. Thus, the crude product was recrystallized from acetonitrile to yield **2a** as a white solid in 83% isolated yield. We also investigated the performances of other electrophiles such as chloramine-T and *N*-chlorophthalimide, but they proved to be less effective than NCS (Table 1, entries 15 and 16).

Table 1. Optimization of Reaction Conditions

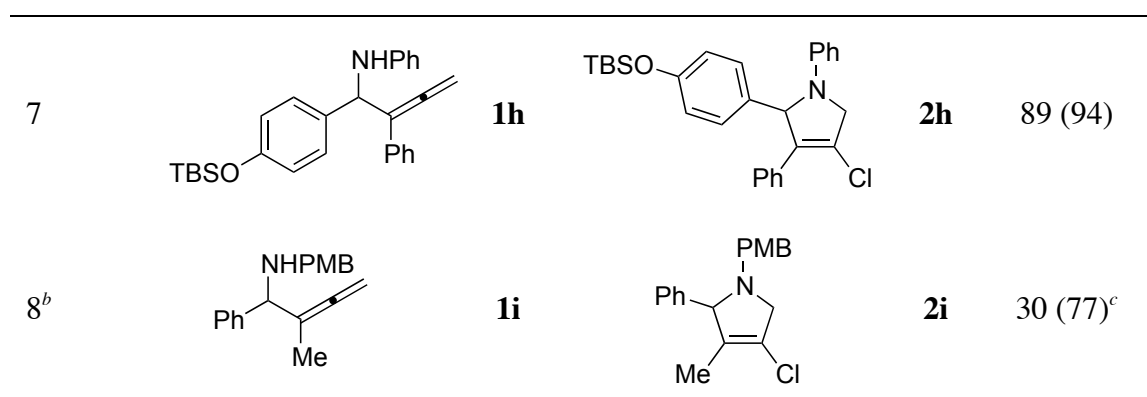
entry	X^+ /base (mol%)	[Ag] (mol%)	yield (%) ^a		
			2	3a	
1	NBS/–	20	2a'	14	52
2 ^b	NBS/–	20	2a'	32	68
3 ^b	NBS/–	100	2a'	32	67
4 ^c	NBS/–	20	2a'	0	0
5	NCS/	20	2a	91	11
6	NCS/DBU (150)	20	2a	0	2
7	NCS/ Et_3N (150)	20	2a	0	6
8	NCS/ <i>N</i> -methylimidazole (150)	20	2a	16	0
9	NCS/pyridine (150)	20	2a	70	21
10	NCS/2,6-di- <i>tert</i> -butylpyridine (150)	20	2a	91	9
11	NCS/2,6-lutidine (150)	20	2a	98	1
12	NCS/ K_2CO_3 (150)	20	2a	49	0
13	NCS/ NaO^tBu (150)	20	2a	3	43
14 ^b	NCS/2,6-lutidine (40)	10	2a	99 (83) ^d	1
15	chloramine-T/–	20	2a	33	49
16 ^b	<i>N</i> -chlorophthalimide/2,6-lutidine (40)	10	2a	83	1

^a Determined by 1H NMR spectroscopy. ^b At 80 °C. ^c With NBS (2.0 equiv). ^d Isolated yield.

Having established the optimal conditions, we explored the scope of the reaction. Various α -aminoallene substrates **1** successfully underwent the silver-catalyzed intramolecular chloroamination to yield the corresponding products in good to excellent yields.¹² Moreover, the reaction tolerates an array of functional groups such as keto, ester, and cyano (Table 2, entries 1–3). Carbon–halogen bonds also survive the reaction and are useful for further reactions using the products (Table 2, entries 4 and 5). The reaction occurs under mild conditions, and as a result, even acid-labile functional groups such as acetal and silyl ether are completely tolerated (Table 2, entries 6 and 7). The high functional group tolerance highlights the utility of the cationic silver complexes as an extremely soft and thus carbophilic Lewis acid. *N*-protected substrate **1i** bearing a methyl substituted allene moiety is also a suitable substrate (Table 2, entry 8). In this case, a 4% yield of *N*-chloroamine and unidentified products were also detected. Unfortunately, **2i** is relatively unstable and gradually decomposes.

Table 2. Scope of the Substrate

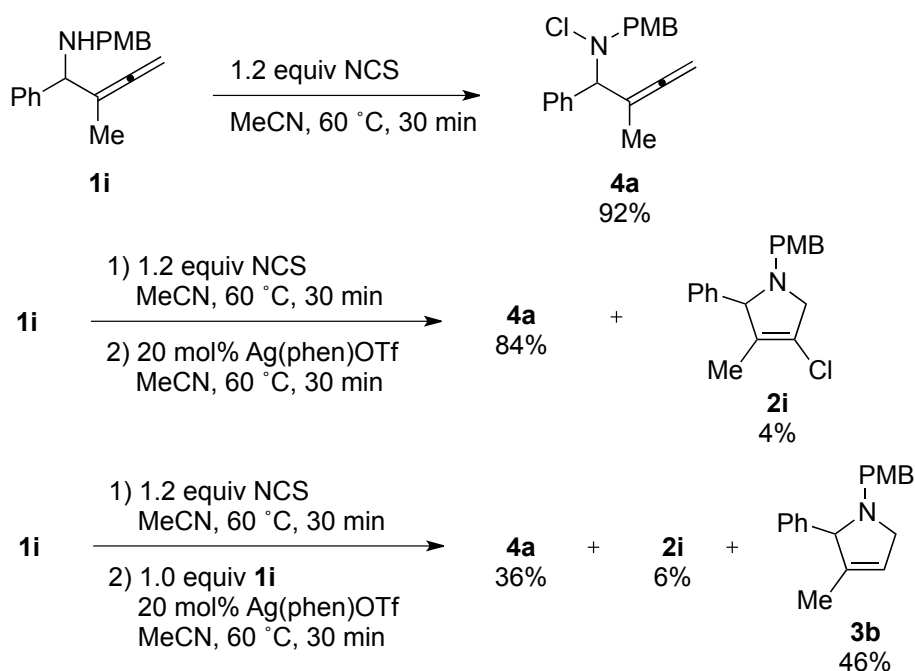
entry	substrate	product	yield (%) ^a
1	1b	2b	91 (96)
2	1c	2c	82 (99)
3	1d	2d	91 (98)
4	1e	2e	76 (98)
5	1f	2f	77 (99)
6	1g	2g	94 (94)



^a Yield is of isolated product. Yields determined by ¹H NMR spectroscopy are given in parentheses. ^b In the absence of 2,6-lutidine. ^c Four percent of *N*-chloroamine and unidentified products were detected.

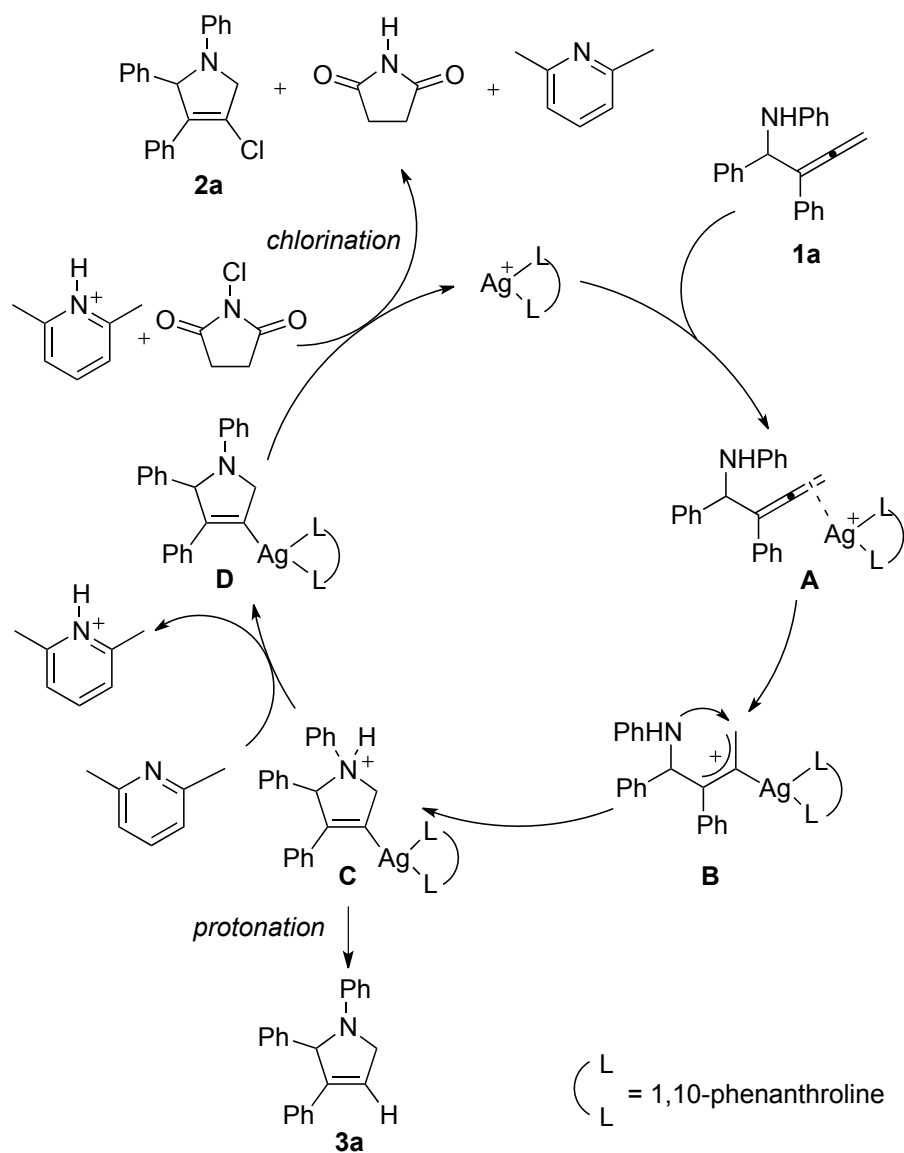
To gain insight into the mechanism, we conducted the following experiments (Scheme 2). Based on the fact that a small amount of *N*-chloroamine **4a** was observed in the reaction of **1i**, we considered that the chloroamination reaction could proceed through a pathway starting from in situ generated **4a**.¹³ In fact, the reaction of **1i** with NCS in the absence of the silver catalyst gave **4a** in 92% NMR yield. However, when **4a** was heated with the silver catalyst, the chloroamination product **2i** was hardly obtained. Next, we suspected that **4a** might act as the actual chlorinating agent instead of NCS. To confirm this hypothesis, **4a** was reacted with **1i** under silver catalysis, which afforded **2i** in only 6% yield. These results suggest that *N*-chloroamine **4a** is not involved in the reaction either as a starting material or as a chlorinating reagent.

Scheme 2.



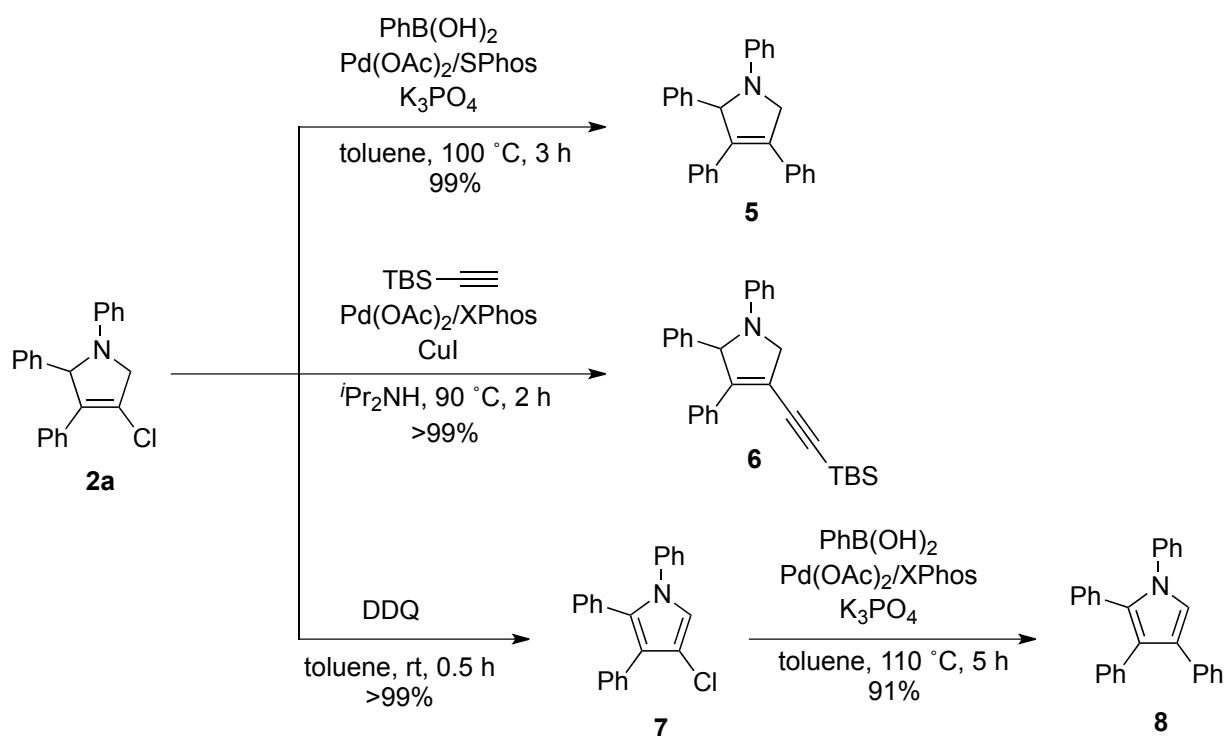
Although mechanistic details require further studies, our proposed catalytic cycle is shown in Scheme 3. The reaction is initiated by the coordination of the cationic silver complex to the allenic π -bond of **1a** to give the π -complex **A**. Subsequently, intramolecular nucleophilic attack of the nitrogen atom on the terminal carbon of **B** occurs to form the vinyl-silver intermediate **C**. 2,6-Lutidine that will be more basic than **3a** reacts with **C** to form **D**, which significantly retards the protonation pathway.¹⁴ Then, **D** reacts with NCS to produce the chloroamination product **2a** and regenerate the cationic silver catalyst.

Scheme 3.



The chloroamination products are versatile synthetic intermediates that can be easily transformed into other azacycles (Scheme 4). For example, treatment of **2a** with phenylboronic acid under palladium catalysis affords tetrasubstituted 3-pyrroline **5** almost completely.¹⁵ **2a** also underwent the Sonogashira cross-coupling reaction to furnish enyne **6**. Moreover, oxidation of **2a** mediated by DDQ and subsequent Suzuki-Miyaura cross-coupling yielded tetrasubstituted pyrrole **8**.

Scheme 4.



Conclusion

The author has developed a silver-catalyzed intramolecular chloroamination of allenes. This process proceeds under mild conditions and can tolerate a variety of functional groups such as keto, ester, cyano, halogen, acetal, and silyl ether. The high functional group tolerance highlights the utility of the silver catalyst as an extremely soft and carbophilic Lewis acid. The chloroamination products are versatile synthetic intermediates and can be easily transformed into functionalized 3-pyrroline and pyrrole derivatives.

Experimental Section

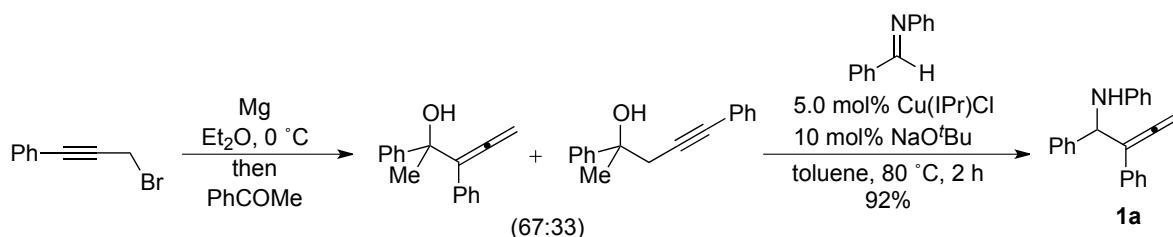
Instrumentation

^1H NMR (500 MHz) and ^{13}C NMR (125.7 MHz) spectra were taken on a Varian UNITY INOVA 500 spectrometer. Chemical shifts (δ) are in parts per million relative to tetramethylsilane at 0.00 ppm for ^1H and relative to CDCl_3 at 77.23 ppm for ^{13}C unless otherwise noted. Mass spectra were determined on a JEOL Mstation 700 spectrometer. IR spectra were determined on a SHIMADZU IR Affinity-1 spectrometer. Melting points were determined using a YANAKO MP-500D. Preparative recycling gel permeation chromatography (GPC) was performed with JAI LC-908 equipped with JAIGEL-1H and -2H columns (toluene as an eluent). Kanto Chemical silica gel (spherical 40–100 mm) was used for column chromatography. Elemental analyses were carried out at the Elemental Analysis Center of Kyoto University.

Materials

N-chlorosuccinimide was purchased from Tokyo Chemical Industry Co., Ltd. Acetonitrile was purchased from Wako Pure Chemical Co. 2,6-Lutidine was purchased from Nacalai Tesque. $\text{Ag}(\text{phen})\text{OTf}$ was prepared according to the reported method.⁹ α -Aminoallenes **1a–1h** were prepared as shown below. α -Aminoallene **1i** was prepared according to the reported method.¹⁶ All other reagents were available from commercial sources and were used without further purification.

Representative procedure for preparation of **1**



Compound 1a: Benzimine (90.6 mg, 0.50 mmol), Cu(IPr)Cl (12.0 mg, 0.025 mmol) and NaO^tBu (4.8 mg, 0.050 mmol) were placed in an oven-dried 30-mL reaction flask equipped with a magnetic stirrer bar and a Dimroth condenser. Under argon, to the flask was added a solution of a 67:33 mixture of allenic alcohol and homopropargyl alcohol (236.3 mg, 1.0 mmol) in toluene (3.0 mL). Then the reaction mixture was heated at 80 °C for 2 h. After cooled to room temperature, ethyl acetate (5 mL) and NH₄Cl aq (5 mL) were added. The organic layer was separated and the aqueous layer was extracted twice with ethyl acetate (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with activated alumina. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 10:1) to give **1a** (137.0 mg, 92%) as a white solid.

Experimental Procedures

Representative Procedure for Silver-Catalyzed Intramolecular Chloroamination of Allenes.

Compound 2a: Aminoallene **1a** (148.6 mg, 0.50 mmol), *N*-chlorosuccinimide (86.8 mg, 0.65 mmol), and Ag(phen)OTf (21.9 mg, 0.050 mmol) were placed in an oven-dried test tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube were added MeCN (4.0 mL) and 2,6-lutidine (23.3 mL, 0.20 mmol). Then the reaction mixture was heated at 80 °C for 30 min. After cooled to room temperature, the mixture was passed through a short activated alumina column with CH₂Cl₂ and concentrated. To the residue were added CH₂Cl₂ (5 mL) and 8% ammonia solution (5 mL). The organic layer was separated and the aqueous layer was extracted twice with CH₂Cl₂ (5 mL). Combined organic layer was dried over Na₂SO₄ and filtered with activated alumina. The filtrate was concentrated, and the residue was purified by recrystallization from MeCN to give **2a** (138.0 mg, 83%) as a white solid.

Products **2a**, **2c**, **2e**, **2f** were purified by recrystallization, and **2b**, **2d**, **2g**, **2h**, **2i** were by preparative GPC.

Procedure for Transformation of 2a into 5.

2a (165.9 mg, 0.50 mmol), phenylboronic acid (91.5 mg, 0.75 mmol), Pd(OAc)₂ (5.5 mg, 0.025 mmol), SPhos (20.5 mg, 0.050 mmol), and K₃PO₄ (212.5 mg, 1.0 mmol) were placed in an oven-dried test tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube was added toluene (2.0 mL), and the mixture was stirred for 3 h at 100 °C. After cooled to room temperature, the mixture was passed through a short activated alumina column with EtOAc. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 10:1) to give **5** (185.5 mg, 99%) as a white solid.

Procedure for Transformation of 2a into 6.

2a (165.9 mg, 0.50 mmol), Pd(OAc)₂ (5.5 mg, 0.025 mmol), XPhos (24.0 mg, 0.050 mmol), and CuI (9.6 mg, 0.050 mmol) were placed in an oven-dried test tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube was added a solution of silyl acetylene (140.5 mg, 1.0 mmol) in diisopropylamine (4.0 mL), and the mixture was stirred for 2 h at 90 °C. After cooled to room temperature, the mixture was passed through a short activated alumina column with EtOAc. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 30:1) to give **6** (218.4 mg, >99%) as a white solid.

Procedure for Transformation of 2a into 7.

2a (165.9 mg, 0.50 mmol) and DDQ (147.6 mg, 0.65 mmol) were placed in an oven-dried test tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube was added toluene (4.0 mL), and the mixture was stirred for 30 min at room temperature. Then, the mixture was passed through a short activated alumina column with

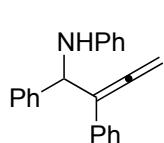
CH_2Cl_2 . The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/EtOAc, 10:1) to give **7** (165.4 mg, >99%) as a white solid.

Procedure for Transformation of **7** into **8**.

2a (164.9 mg, 0.50 mmol), phenylboronic acid (91.5 mg, 0.75 mmol), $\text{Pd}(\text{OAc})_2$ (5.5 mg, 0.025 mmol), XPhos (24.0 mg, 0.05 mmol), and K_3PO_4 (212.5 mg, 1.0 mmol) were placed in an oven-dried test tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube was added toluene (4.0 mL), and the mixture was stirred for 5 h at 110 °C. After cooled to room temperature, the mixture was passed through a short activated alumina column with CH_2Cl_2 . The filtrate was concentrated, and the residue was purified by column chromatography on silica gel (hexane/ CHCl_3 , 4:1) to give **8** (168.1 mg, 91%) as a white solid.

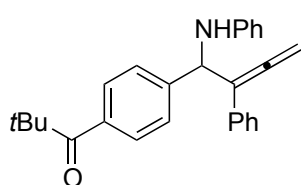
Characterization Data of New Compounds

1,2-Diphenyl-2,3-butadienylaniline (**1a**):



IR (nujol) 3425, 1929, 1828, 1597, 1458, 1312, 1250 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.24 (d, $J = 6.0$ Hz, 1H), 5.05 (dd, $J = 12.0, 2.5$ Hz, 1H), 5.09 (dd, $J = 12.0, 2.0$ Hz, 1H), 5.43 (ddd, $J = 6.0, 2.5, 2.0$ Hz, 1H), 6.57–6.61 (m, 2H), 6.67–6.72 (m, 1H), 7.10–7.47 (m, 12H); ^{13}C NMR (CDCl_3) δ 58.10, 81.03, 108.82, 113.67, 117.86, 126.82, 127.25, 127.72, 127.77, 128.72, 128.74, 129.32, 134.95, 141.59, 147.24, 209.38 Found: C, 89.11; H, 6.61%. Calcd for $\text{C}_{22}\text{H}_{19}\text{N}$: C, 88.85; H, 6.44%. m.p.: 97–98 °C.

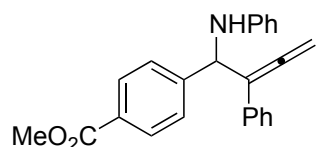
2-Phenyl-1-(4-pivaloylphenyl)-2,3-butadienylaniline (**1b**):



IR (nujol) 3386, 2952, 1937, 1678, 1606, 1594, 1517, 1494 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.34 (s, 9H), 4.27 (br s, 1H), 5.07 (d, $J = 2.5$ Hz, 2H), 5.46 (br s, 1H), 6.57–6.61 (m, 2H), 6.70–6.74 (m, 1H), 7.12–7.16 (m,

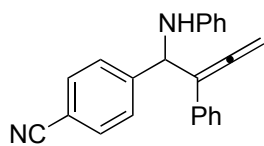
2H), 7.19–7.23 (m, 1H), 7.27–7.32 (m, 2H), 7.35–7.39 (m, 2H), 7.46–7.50 (m, 2H), 7.66–7.70 (m, 2H); ^{13}C NMR (CDCl_3) δ 28.27, 44.35, 57.89, 81.26, 108.72, 113.71, 118.17, 126.77, 127.36, 127.46, 128.51, 128.85, 129.41, 134.62, 137.78, 144.77, 147.01, 208.85, 209.32. HRMS (ESI) Calcd for $\text{C}_{27}\text{H}_{27}\text{NO}$: m/z 382.2165 ($[\text{M}+\text{H}]^+$), found: 382.2154 ($[\text{M}+\text{H}]^+$). m.p.: 127–129 °C.

1-(4-Methoxycarbonylphenyl)-2-phenyl-2,3-butadienylaniline (1c):



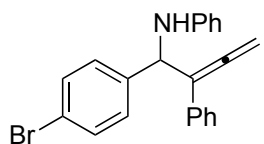
IR (nujol) 3333, 1936, 1697, 1605, 1458, 1373, 1288, 1111 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.89 (s, 3H), 4.30 (d, $J = 6.0$ Hz, 1H), 5.03 (dd, $J = 14.5, 2.0$ Hz, 1H), 5.06 (dd, $J = 14.5, 2.0$ Hz, 1H), 5.48 (ddd, $J = 6.0, 2.0, 2.0$ Hz, 1H), 6.55–6.59 (m, 2H), 6.69–6.74 (m, 1H), 7.11–7.16 (m, 2H), 7.19–7.23 (m, 1H), 7.27–7.31 (m, 2H), 7.35–7.39 (m, 2H), 7.49–7.53 (m, 2H), 7.97–8.01 (m, 2H); ^{13}C NMR (CDCl_3) δ 52.21, 57.99, 81.30, 108.76, 113.66, 118.21, 126.73, 127.49, 127.66, 128.86, 129.41, 129.54, 130.00, 134.47, 146.90, 147.01, 167.10, 209.28. Found: C, 81.05; H, 6.10%. Calcd for $\text{C}_{24}\text{H}_{21}\text{NO}_2$: C, 81.10; H, 5.96%. m.p.: 114–116 °C.

1-(4-Cyanophenyl)-2-phenyl-2,3-butadienylaniline (1d):



IR (nujol) 3399, 2954, 2224, 1933, 1600, 1504, 1430 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.30 (d, $J = 4.5$ Hz, 1H), 5.02 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.06 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.48 (ddd, $J = 4.5, 2.5, 2.5$ Hz, 1H), 6.52–6.56 (m, 2H), 6.71–6.76 (m, 1H), 7.12–7.16 (m, 2H), 7.21–7.26 (m, 1H), 7.28–7.33 (m, 2H), 7.35–7.38 (m, 2H), 7.52–7.56 (m, 2H), 7.58–7.62 (m, 2H); ^{13}C NMR (CDCl_3) δ 57.96, 81.52, 108.74, 111.46, 113.64, 118.54, 119.01, 126.65, 127.71, 128.33, 128.97, 129.51, 132.48, 134.12, 146.61, 147.41, 209.23. Found: C, 85.52; H, 5.80%. Calcd for $\text{C}_{23}\text{H}_{18}\text{N}_2$: C, 85.68; H, 5.63%. m.p.: 100–104 °C.

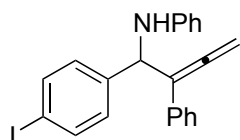
1-(4-Bromophenyl)-2-phenyl-2,3-butadienylaniline (1e):



IR (nujol) 3418, 1936, 1605, 1458, 1373, 1311, 1180 cm^{-1} ; ^1H NMR

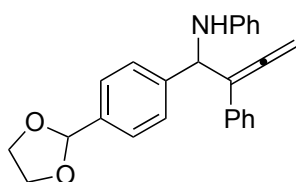
(CDCl₃) d 4.23 (d, $J = 5.5$ Hz, 1H), 5.05 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.08 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.39 (ddd, $J = 5.5, 2.5, 2.5$ Hz, 1H), 6.54–6.58 (m, 2H), 6.69–6.73 (m, 1H), 7.11–7.15 (m, 2H), 7.18–7.24 (m, 1H), 7.26–7.33 (m, 4H), 7.34–7.38 (m, 2H), 7.41–7.45 (m, 2H); ¹³C NMR (CDCl₃) d 57.61, 81.32, 108.80, 113.68, 118.18, 121.48, 126.75, 127.46, 128.85, 129.40, 129.43, 131.78, 134.56, 140.78, 146.95, 209.25. Found: C, 70.26; H, 5.12%. Calcd for C₂₂H₁₈BrN: C, 70.22; H, 4.82%.

1-(4-Iodophenyl)-2-phenyl-2,3-butadienylaniline (1f):



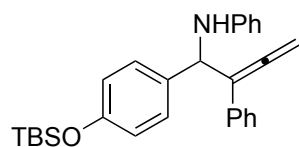
IR (nujol) 3416, 1940, 1605, 1458, 1373, 1304 cm⁻¹; ¹H NMR (CDCl₃) d 4.22 (d, $J = 5.5$ Hz, 1H), 5.06 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.08 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.37 (ddd, $J = 5.5, 2.5, 2.5$ Hz, 1H), 6.54–6.57 (m, 2H), 6.68–6.73 (m, 1H), 7.10–7.15 (m, 2H), 7.16–7.22 (m, 3H), 7.26–7.30 (m, 2H), 7.34–7.37 (m, 2H), 7.60–7.64 (m, 2H); ¹³C NMR (CDCl₃) d 57.68, 81.34, 93.13, 108.73, 113.67, 118.16, 126.73, 127.45, 128.84, 129.39, 129.70, 134.54, 137.74, 141.49, 146.93, 209.23. Found: C, 62.66; H, 4.04%. Calcd for C₂₂H₁₈IN: C, 62.42; H, 4.29%.

2-Phenyl-1-(4-tetrahydropyranylphenyl)-2,3-butadienylaniline (1g):



IR (nujol) 3364, 1929, 1697, 1597, 1458, 1373, 1319, 1080 cm⁻¹; ¹H NMR (CDCl₃) d 3.98–4.05 (m, 2H), 4.08–4.15 (m, 2H), 4.24 (br d, $J = 5.5$ Hz, 1H), 5.05 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.08 (dd, $J = 12.5, 2.5$ Hz, 1H), 5.44 (ddd, $J = 5.5, 2.5, 2.5$ Hz, 1H), 5.77 (s, 1H), 6.56–6.60 (m, 2H), 6.67–6.71 (m, 1H), 7.10–7.14 (m, 2H), 7.17–7.21 (m, 1H), 7.25–7.29 (m, 2H), 7.35–7.38 (m, 2H), 7.42–7.48 (m, 4H); ¹³C NMR (CDCl₃) d 57.89, 65.50, 81.17, 103.79, 108.71, 113.65, 117.91, 126.78, 126.90, 127.28, 127.78, 128.75, 129.31, 134.79, 137.26, 142.74, 147.12, 209.30. Found: C, 81.00; H, 6.35%. Calcd for C₂₅H₂₃NO₂: C, 81.27; H, 6.27%. m.p.: 96–99 °C.

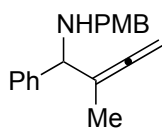
1-(4-tert-Butyldimethylsiloxyphenyl)-2-phenyl-2,3-butadienylaniline (1h):



IR (neat) 3414, 3052, 2956, 2886, 1940, 1889, 1599, 1508, 1427 cm^{-1} ;

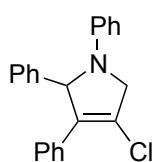
^1H NMR (CDCl_3) δ 0.18 (s, 6H), 0.97 (s, 9H), 4.19 (br s, 1H), 5.03 (dd, $J = 12.0, 2.5$ Hz, 1H), 5.08 (dd, $J = 12.0, 2.5$ Hz, 1H), 5.33–5.37 (m, 1H), 6.57–6.61 (m, 2H), 6.66–6.71 (m, 1H), 6.76–6.80 (m, 2H), 7.10–7.20 (m, 3H), 7.24–7.37 (m, 6H); ^{13}C NMR (CDCl_3) δ -4.21, 18.38, 25.87, 57.64, 80.91, 108.89, 113.71, 117.76, 120.25, 126.87, 127.17, 128.68, 128.89, 129.28, 134.24, 135.08, 147.34, 155.28, 209.36. Found: C, 78.63; H, 7.87%. Calcd for $\text{C}_{28}\text{H}_{33}\text{NOSi}$: C, 78.64; H, 7.78%.

N-(4-Methoxybenzyl)-2-methyl-1-phenyl-2,3-butadienylamine (1i):



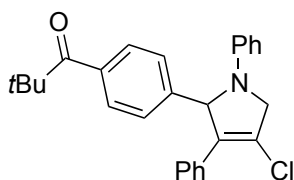
IR (neat) 2916, 2831, 1960, 1612, 1512, 1450, 1303, 1250, 1034 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.54 (dd, $J = 3.0, 3.0$ Hz, 3H), 1.75 (br s, 1H), 3.64 (d, $J = 13.0$ Hz, 1H), 3.68 (d, $J = 13.0$ Hz, 1H), 3.80 (s, 3H), 4.11 (dd, $J = 3.0, 3.0$ Hz, 1H), 4.80–4.87 (m, 2H), 6.83–6.87 (m, 2H), 7.20–7.27 (m, 3H), 7.30–7.36 (m, 4H); ^{13}C NMR (CDCl_3) δ 15.61, 50.91, 55.43, 64.22, 76.41, 101.42, 113.91, 127.42, 127.76, 128.45, 129.58, 132.69, 142.38, 158.77, 205.93. Found: C, 81.73; H, 7.58%. Calcd for $\text{C}_{19}\text{H}_{21}\text{NO}$: C, 81.68; H, 7.58%.

4-Chloro-1,2,3-triphenyl-3-pyrroline (2a):



IR (nujol) 1659, 1597, 1497, 1366, 1250 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.49 (dd, $J = 13.5, 3.0$ Hz, 1H), 4.73 (dd, $J = 13.5, 6.5$ Hz, 1H), 5.73 (dd, $J = 6.5, 3.0$ Hz, 1H), 6.53–6.57 (m, 2H), 6.66–6.70 (m, 1H), 7.11–7.29 (m, 12H); ^{13}C NMR (CDCl_3) δ 59.75, 72.29, 112.03, 117.02, 122.60, 127.43, 127.80, 128.31, 128.34, 128.68, 128.70, 129.38, 132.07, 137.85, 141.13, 145.72. Found: C, 79.44; H, 5.65%. Calcd for $\text{C}_{22}\text{H}_{18}\text{ClN}$: C, 79.63; H, 5.47%. m.p.: 162–166 $^{\circ}\text{C}$.

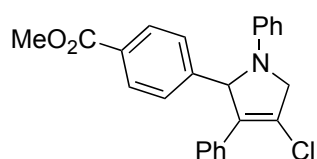
4-Chloro-1,3-diphenyl-2-(4-pivaloylphenyl)-3-pyrroline (2b):



IR (nujol) 2970, 2846, 1682, 1664, 1597, 1505, 1447 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.27 (s, 9H), 4.50 (dd, $J = 13.5, 3.0$ Hz, 1H), 4.74 (dd, $J =$

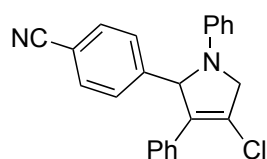
13.5, 6.5 Hz, 1H), 5.78 (dd, $J = 6.5, 3.0$ Hz, 1H), 6.51–6.55 (m, 2H), 6.68–6.73 (m, 1H), 7.15–7.20 (m, 2H), 7.20–7.30 (m, 7H), 7.54–7.58 (m, 2H); ^{13}C NMR (CDCl_3) δ 28.20, 44.26, 59.79, 71.91, 112.05, 117.32, 123.06, 127.05, 128.45, 128.50, 128.58, 128.62, 129.47, 137.75, 137.38, 137.81, 144.27, 145.55, 208.65. HRMS (ESI) Calcd for $\text{C}_{27}\text{H}_{26}\text{ClNO}$: m/z 416.1776 ($[\text{M}+\text{H}]^+$), found: 416.1768 ($[\text{M}+\text{H}]^+$). m.p.: 64–66 °C.

4-Chloro-1,3-diphenyl-2-(4-methoxycarbonylphenyl)-3-pyrroline (2c):



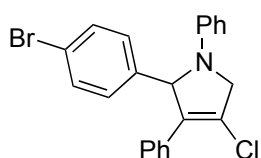
IR (nujol) 1720, 1659, 1597, 1504, 1466, 1366, 1281, 1180, 1103 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.84 (s, 3H), 4.52 (dd, $J = 13.5, 3.0$ Hz, 1H), 4.76 (dd, $J = 13.5, 6.5$ Hz, 1H), 5.80 (dd, $J = 6.5, 3.0$ Hz, 1H), 6.50–6.54 (m, 2H), 6.68–6.72 (m, 1H), 7.14–7.19 (m, 2H), 7.20–7.23 (m, 2H), 7.25–7.32 (m, 5H), 7.85–7.88 (m, 2H); ^{13}C NMR (CDCl_3) δ 52.20, 59.80, 72.05, 112.06, 117.41, 123.19, 127.41, 128.51, 128.55, 128.61, 129.48, 129.77, 130.13, 131.69, 137.34, 145.48, 146.53, 166.94. Found: C, 73.86; H, 5.28%. Calcd for $\text{C}_{24}\text{H}_{20}\text{ClNO}_2$: C, 73.94; H, 5.17%. m.p.: 155–157 °C.

4-Chloro-2-(4-cyanophenyl)-1,3-diphenyl-3-pyrroline (2d):



IR (nujol) 2954, 2226, 1659, 1505, 1463, 1446, 1366 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.50 (dd, $J = 13.5, 3.0$ Hz, 1H), 4.74 (dd, $J = 13.5, 6.5$ Hz, 1H), 5.80 (dd, $J = 6.5, 3.0$ Hz, 1H), 6.46–6.50 (m, 2H), 6.70–6.75 (m, 1H), 7.15–7.23 (m, 4H), 7.28–7.35 (m, 5H), 7.44–7.48 (m, 2H); ^{13}C NMR (CDCl_3) δ 59.81, 71.84, 111.75, 112.05, 117.73, 118.73, 123.58, 127.99, 128.51, 128.63, 128.73, 129.56, 131.36, 132.61, 136.95, 145.21, 146.79. HRMS (ESI) Calcd for $\text{C}_{23}\text{H}_{17}\text{ClN}_2$: m/z 357.1153 ($[\text{M}+\text{H}]^+$), found: 357.1146 ($[\text{M}+\text{H}]^+$). m.p.: 118–121 °C.

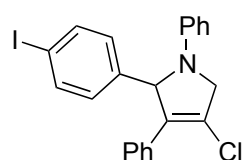
2-(4-Bromophenyl)-4-chloro-1,3-diphenyl-3-pyrroline (2e):



IR (nujol) 1666, 1597, 1466, 1373, 1242, 1134, 1003 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.48 (dd, $J = 13.5, 3.0$ Hz, 1H), 4.72 (dd, $J = 13.5, 6.5$ Hz, 1H),

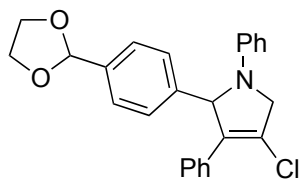
5.71 (dd, $J = 6.5, 3.0$ Hz, 1H), 6.50–6.53 (m, 2H), 6.68–6.73 (m, 1H), 7.09–7.13 (m, 2H), 7.15–7.20 (m, 2H), 7.21–7.33 (m, 7H); ^{13}C NMR (CDCl_3) δ 59.75, 71.68, 112.08, 117.38, 121.61, 122.97, 128.51, 128.52, 128.61, 129.07, 129.47, 131.77, 131.91, 137.40, 140.32, 145.49. Found: C, 64.45; H, 4.34%. Calcd for $\text{C}_{22}\text{H}_{17}\text{BrClN}$: C, 64.33; H, 4.17%. m.p.: 155–158 °C.

4-Chloro-1,3-diphenyl-2-(4-iodophenyl)-3-pyrroline (2f):



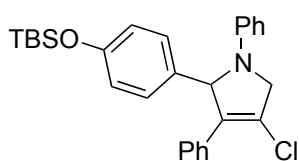
IR (nujol) 1659, 1597, 1458, 1373, 1134, 1003 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.48 (dd, $J = 13.5, 2.5$ Hz, 1H), 4.72 (dd, $J = 13.5, 6.5$ Hz, 1H), 5.70 (dd, $J = 6.5, 2.5$ Hz, 1H), 6.49–6.53 (m, 2H), 6.68–6.72 (m, 1H), 6.96–7.00 (m, 2H), 7.14–7.19 (m, 2H), 7.22–7.32 (m, 5H), 7.49–7.52 (m, 2H); ^{13}C NMR (CDCl_3) δ 59.77, 71.76, 93.31, 112.08, 117.38, 120.28, 123.00, 128.52, 128.62, 129.33, 129.47, 131.77, 137.37, 137.85, 141.04, 145.49. Found: C, 57.64; H, 3.52%. Calcd for $\text{C}_{22}\text{H}_{17}\text{ClIN}$: C, 57.73; H, 3.74%. m.p.: 152–154 °C.

4-Chloro-1,3-diphenyl-2-(4-tetrahydropyranylphenyl)-3-pyrroline (2g):



IR (nujol) 2957, 2930, 2840, 2727, 1600, 1505, 1464 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.92–4.00 (m, 2H), 4.02–4.10 (m, 2H), 4.48 (dd, $J = 13.5, 3.0$ Hz, 1H), 4.74 (dd, $J = 13.5, 6.5$ Hz, 1H), 5.67 (s, 1H), 5.77 (dd, $J = 6.5, 3.0$ Hz, 1H), 6.51–6.55 (m, 2H), 6.65–6.70 (m, 1H), 7.12–7.17 (m, 2H), 7.21–7.33 (m, 9H); ^{13}C NMR (CDCl_3) δ 59.76, 65.42, 65.46, 71.94, 103.71, 112.06, 117.12, 122.74, 126.96, 127.47, 128.39, 128.41, 128.65, 129.39, 131.92, 137.30, 137.62, 142.31, 145.61. HRMS (ESI) Calcd for $\text{C}_{25}\text{H}_{22}\text{ClINO}_2$: m/z 404.1412 ($[\text{M}+\text{H}]^+$), found: 404.1394 ($[\text{M}+\text{H}]^+$). m.p.: 82–84 °C.

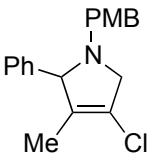
2-(4-tert-Butyldimethylsiloxyphenyl)-4-chloro-1,3-diphenyl-3-pyrroline (2h):



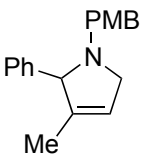
IR (neat) 3059, 3029, 2957, 2827, 1723, 1664, 1599, 1502, 1464, 1367 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.12 (s, 6H), 0.92 (s, 9H), 4.46 (dd, $J =$

13.5, 2.5 Hz, 1H), 4.70 (dd, $J = 13.5, 6.0$ Hz, 1H), 5.65 (dd, $J = 6.0, 2.5$ Hz, 1H), 6.54–6.58 (m, 2H), 6.65–6.70 (m, 3H), 7.07–7.11 (m, 2H), 7.14–7.20 (m, 4H), 7.22–7.28 (m, 3H); ^{13}C NMR (CDCl_3) δ –4.27, 18.35, 25.82, 59.62, 71.97, 112.11, 116.93, 120.31, 122.32, 128.23, 128.27, 128.53, 128.73, 129.33, 132.23, 133.81, 138.06, 145.88, 155.21. HRMS (ESI) Calcd for $\text{C}_{28}\text{H}_{32}\text{ClNOSi}$: m/z 462.2014 ($[\text{M}+\text{H}]^+$), found: 462.1999 ($[\text{M}+\text{H}]^+$).

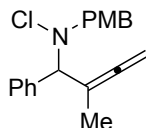
4-Chloro-1-(4-methoxybenzyl)-3-methyl-2-phenyl-3-pyrroline (2i):

 IR (neat) 3062, 2952, 2777, 1676, 1612, 1512, 1453 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.42–1.45 (m, 3H), 3.39–3.46 (m, 1H), 3.46 (d, $J = 13.0$ Hz, 1H), 3.66–3.73 (m, 1H), 3.77 (s, 3H), 3.80 (d, $J = 13.0$ Hz, 1H), 4.41 (br s, 1H), 6.78–6.83 (m, 2H), 7.13–7.18 (m, 2H), 7.26–7.31 (m, 1H), 7.32–7.40 (m, 4H); ^{13}C NMR (CDCl_3) δ 11.57, 55.42, 56.97, 61.53, 76.80, 113.84 (two signals merged), 123.04, 127.91, 128.51 (two signals merged), 128.60, 129.90, 134.13, 158.89. HRMS (ESI) Calcd for $\text{C}_{19}\text{H}_{20}\text{ClNO}$: m/z 314.1306 ($[\text{M}+\text{H}]^+$), found: 314.1309 ($[\text{M}+\text{H}]^+$).

1-(4-Methoxybenzyl)-3-methyl-2-phenyl-3-pyrroline (3b):

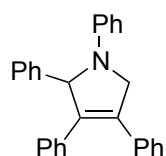
 IR (neat) 3060, 2950, 2772, 1612, 1586, 1513, 1453 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.42–1.45 (m, 3H), 3.20–3.26 (m, 1H), 3.46 (d, $J = 13.0$ Hz, 1H), 3.61–3.67 (m, 1H), 3.78 (s, 3H), 3.81 (d, $J = 13.0$ Hz, 1H), 4.31–4.36 (m, 1H), 5.47–5.50 (m, 1H), 6.78–6.82 (m, 2H), 7.14–7.18 (m, 2H), 7.24–7.28 (m, 1H), 7.32–7.36 (m, 2H), 7.36–7.40 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.42, 55.43, 57.08, 58.36, 77.27, 113.71, 121.67, 127.35, 128.32, 128.62, 129.85, 132.22, 140.65, 142.67, 158.64. HRMS (ESI) Calcd for $\text{C}_{19}\text{H}_{21}\text{NO}$: m/z 280.1696 ($[\text{M}+\text{H}]^+$), found: 280.1692 ($[\text{M}+\text{H}]^+$).

N-Chloro-N-(4-methoxybenzyl)-2-methyl-1-phenyl-2,3-butadienylamine (4a):



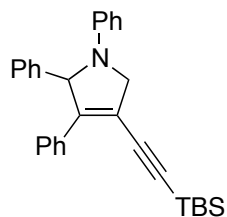
IR (neat) 3062, 2955, 2836, 1958, 1613, 1586, 1513, 1493, 1453 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.71 (dd, $J = 3.0, 3.0$ Hz, 3H), 3.80 (s, 3H), 3.98 (d, $J = 13.5$ Hz, 1H), 4.09 (d, $J = 13.5$ Hz, 1H), 4.49 (s, 1H), 4.75–4.83 (m, 2H), 6.86–6.90 (m, 2H), 7.27–7.32 (m, 3H), 7.33–7.38 (m, 2H), 7.42–7.45 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.70, 55.40, 63.89, 75.52, 77.91, 100.42, 113.82, 127.97, 128.18, 128.41, 129.78, 130.42, 139.87, 159.32, 207.85. HRMS (ESI) Calcd for $\text{C}_{19}\text{H}_{20}\text{ClNO}$: m/z 314.1306 ($[\text{M}+\text{H}]^+$), found: 314.1300 ($[\text{M}+\text{H}]^+$).

1,2,3,4-Tetraphenyl-3-pyrroline (5):



IR (nujol) 1597, 1458, 1373, 1258, 1180 cm^{-1} ; ^1H NMR (CDCl_3) δ 4.76 (dd, $J = 14.0, 3.0$ Hz, 1H), 5.06 (dd, $J = 14.0, 6.5$ Hz, 1H), 5.71 (dd, $J = 6.5, 3.0$ Hz, 1H), 6.60–6.64 (m, 2H), 6.64–6.68 (m, 1H), 6.86–6.88 (m, 2H), 7.12–7.23 (m, 15H); ^{13}C NMR (CDCl_3) δ 59.17, 75.23, 112.15, 116.39, 127.47, 127.56, 127.58, 127.75, 127.96, 128.43, 128.47, 128.55, 129.27, 129.32, 131.53, 134.35, 135.45, 139.34, 142.02, 146.12. Found: C, 90.23; H, 6.13%. Calcd for $\text{C}_{28}\text{H}_{23}\text{N}$: C, 90.04; H, 6.21%. m.p.: 138–141 $^{\circ}\text{C}$.

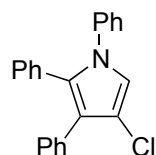
4-tert-Butyldimethylsilylethynyl-1,2,3-triphenyl-3-pyrroline (6):



IR (nujol) 2954, 2141, 1596, 1506, 1366 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.14 (s, 3H), 0.16 (s, 3H), 0.94 (s, 9H), 4.47 (dd, $J = 13.5, 2.5$ Hz, 1H), 4.70 (dd, $J = 13.5, 6.0$ Hz, 1H), 5.89 (dd, $J = 6.0, 2.5$ Hz, 1H), 6.58–6.61 (m, 2H), 6.63–6.67 (m, 1H), 7.08–7.12 (m, 1H), 7.13–7.26 (m, 7H), 7.29–7.32 (m, 2H), 7.58–7.62 (m, 2H); ^{13}C NMR (CDCl_3) δ -4.51, 16.91, 26.29, 59.35, 71.39, 100.31, 100.38, 112.08, 114.91, 116.60, 127.62, 127.82, 128.10, 128.28, 128.42, 128.65, 129.30, 133.30, 141.72, 145.72, 147.80. Found: C, 82.58; H, 7.64%. Calcd for $\text{C}_{30}\text{H}_{33}\text{NSi}$: C, 82.70; H, 7.63%. m.p.:

131–134 °C.

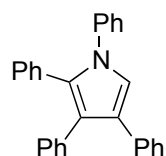
4-Chloro-1,2,3-triphenylpyrrole (7):



IR (nujol) 1682, 1597, 1458, 1373, 1227 cm^{-1} ; ^1H NMR (CDCl_3) d 6.90–6.94 (m, 2H), 7.01 (s, 1H), 7.06–7.15 (m, 5H), 7.19–7.30 (m, 8H); ^{13}C NMR (CDCl_3) d 109.94, 113.19, 120.32, 122.51, 126.09, 126.55, 127.13, 127.25, 128.07, 128.12, 129.14, 130.70, 131.06, 131.48, 133.48, 139.78. Found: C, 79.98; H, 5.15%.

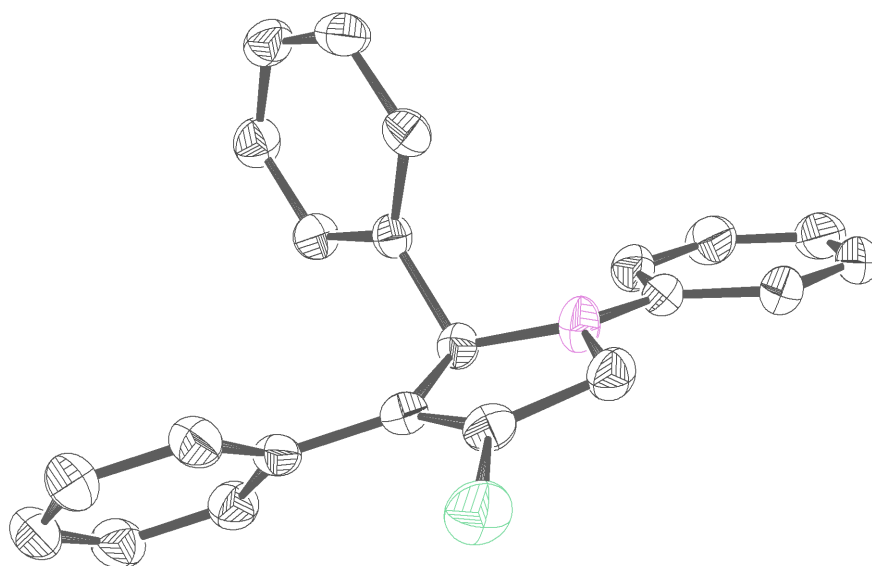
Calcd for $\text{C}_{22}\text{H}_{16}\text{ClN}$: C, 80.11; H, 4.89%. m.p.: 175–178 °C.

1,2,3,4-Tetraphenylpyrrole (8):



IR (nujol) 2966, 2897, 2862, 1594, 1499 cm^{-1} ; ^1H NMR (CDCl_3) d 6.94–6.97 (m, 2H), 7.05–7.12 (m, 5H), 7.12–7.18 (m, 7H), 7.19–7.25 (m, 5H), 7.26–7.30 (m, 2H); ^{13}C NMR (CDCl_3) d 121.50, 123.31, 125.11, 125.90, 125.99, 126.07, 126.76, 126.85, 127.92, 127.98, 128.31, 128.57, 129.05, 131.28 (two signals merged), 131.70, 132.20, 135.53, 135.68, 140.37. Found: C, 90.26; H, 5.91%. Calcd for $\text{C}_{28}\text{H}_{21}\text{N}$: C, 90.53; H, 5.70%. m.p.: 176–177 °C.

Figure 1. ORTEP diagram of **2a**.



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Chapter 3

Li⁺-Catalyzed Nazarov-Type Cyclization of 1-Aryl-2,3-butadien-1-ols: Synthesis of Benzofulvene Derivatives

Lithium hexafluorophosphate proved to be uniquely effective for the Nazarov-type cyclization of 1-aryl-2,3-butadien-1-ols via C–O bond cleavage. This process proceeds under mild conditions and can tolerate a variety of functional groups.

Introduction

The alkylation of aromatic compounds is a synthetically useful transformation for the construction of carbon–carbon bonds.¹ The vast majority of traditional methods has involved the use of alkyl halides and pseudohalides as alkylating reagents in the presence of stoichiometric amounts of Lewis acid catalysts. Accordingly, these methods inevitably produce large amounts of waste products. In terms of atom economy and environmental concerns, employment of alcohols as alkylating reagents is highly desirable. However, direct catalytic substitution of alcohols with aromatic compounds is often problematic because alcohol substrates and/or in situ generated water could deactivate the catalysts. Recently, significant progress has been achieved in the metal-catalyzed alkylation of arenes. In addition to well-documented scandium and lanthanide triflates,² indium,³ iron,⁴ bismuth,⁵ and late transition metals⁶ have been proven to be highly effective for this type of reaction. Nevertheless, to our knowledge, there has been no report on the use of alkali metals as Lewis acids in such reactions despite their abundance, low cost, and nontoxicity.⁷ In Chapter 3, the author investigated the Lewis acidities of alkali metals and found that LiPF₆ was uniquely effective for Nazarov-type cyclization of 1-aryl-2,3-butadien-1-ols via C–O bond cleavage.

Results and Discussion

Initial experiments were performed using tertiary α -allenol **1a** as a model substrate. Treatment of **1a** with 5.0 mol% of lithium triflate in toluene did provide the desired benzofulvene **2a**, albeit in only 9% yield (Table 1, entry 1). To improve the yield, we examined the impact of the counteranion on this reaction. While changing the counteranion from triflate to a non-coordinating anion, perchlorate or tetrafluoroborate did not improve the reaction at all (Table 1, entries 2 and 3), the use of lithium hexafluorophosphate dramatically increased the yield of **2a** to 63% (Table 1, entry 4). The choice of solvent was also crucial to attain high yield.

Screening of various solvents showed that hexane proved to be the optimal solvent, affording **2a** in 87 % isolated yield (Table 1, entry 6). In contrast, the use of coordinating solvents gave poor results probably due to the coordinative solvation to the metal center (Table 1, entries 7–9). In this transformation, 1 equiv of water is released during the course of the reaction. Therefore, we suspected that generation of a protic acid might be occurring by the reaction of LiPF_6 with water. To confirm this hypothesis, we investigated the performances of other hexafluorophosphate salts such as NaPF_6 , KPF_6 , and NH_4PF_6 , resulting in almost no reaction (Table 1, entries 10–12). In addition, even when using HPF_6 as a catalyst, **2a** was observed in only 16% yield (Table 1, entry 13). These results suggest that the current reaction would be catalyzed by a lithium cation, not by a protic acid.

Table 1. Optimization of Reaction Conditions

$\text{1a} \xrightarrow[\text{-H}_2\text{O}]{\text{5.0 mol\% catalyst, solvent, 65 }^\circ\text{C, 1 h}} \text{2a}$

entry	catalyst	solvent	yield (%) ^a
1	LiOTf	toluene	9
2	LiClO ₄	toluene	0
3	LiBF ₄	toluene	1
4	LiPF ₆	toluene	63
5	LiPF ₆	ClCH ₂ CH ₂ Cl	37
6	LiPF ₆	hexane	87 ^b
7	LiPF ₆	CH ₃ NO ₂	8
8	LiPF ₆	THF	0
9	LiPF ₆	CH ₃ CN	1
10	NaPF ₆	hexane	<1
11	KPF ₆	hexane	0
12	NH ₄ PF ₆	hexane	0
13	HPF ₆ (65 wt % in water)	hexane	16

^a Determined by ¹H NMR spectroscopy. ^b Isolated yield.

Having established the optimal conditions, we explored the scope of the reaction. The reaction proceeds smoothly when the aryl group of α -allenols is substituted with electron-donating groups (Table 2, entries 1, 2, and 6). Substrates containing electron-deficient aryl groups also undergo the cyclization to afford the corresponding products in good yields, although higher catalyst loadings are required (Table 2, entries 3–5). Due to the mild and neutral reaction conditions, a variety of functionalities including ether, ester, aryl halide, and silyl ether are well tolerated. In the case of **1h**, the rapid formation of the fused tricyclic benzofulvene **2h** can be achieved due to its enhanced Thorpe-Ingold effect (Table 2, entry 7).

Substrate **1i** containing a *meta*-substituent on the aryl ring reacts to form two regioisomeric products **2i** and **2i'** in close to a 1:1 ratio. (Table 2, entries 8).

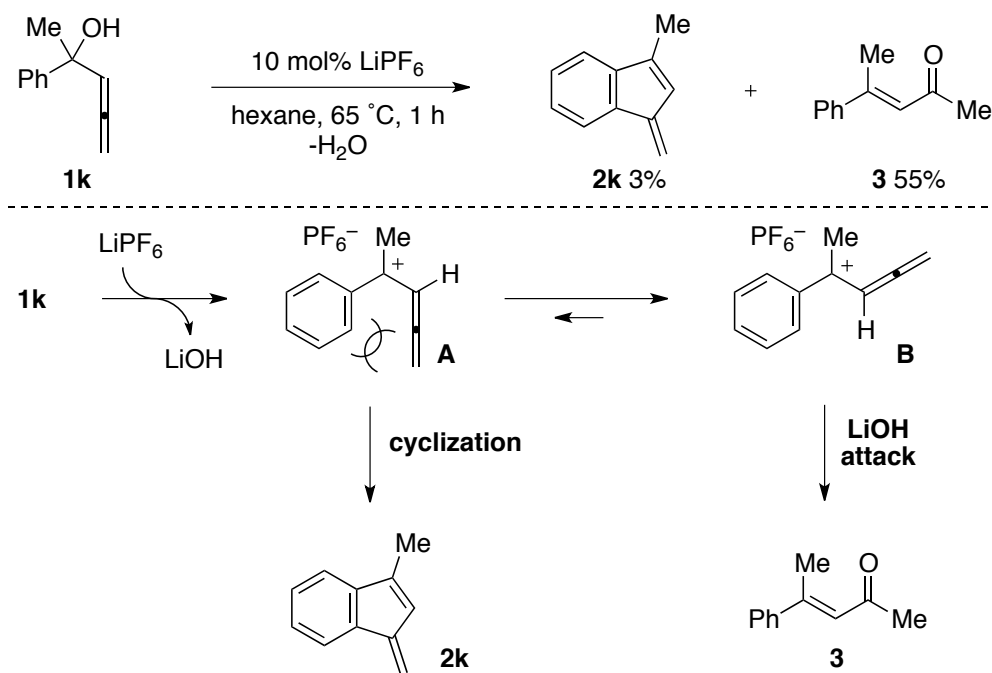
Table 2. Scope of Tertiary α -Allenols^a

entry	substrate	[Li] (mol%)	time (h)	yield of 2 (%) ^b
1	1b R = OMe	5.0	0.5	2b 94
2	1c R = Me	5.0	0.5	2c 80
3 ^c	1d R = CO ₂ Me	10	1	2d 67
4	1e R = CF ₃	20	1	2e 67
5	1f R = Br	10	1	2f 79
6	1g R = OTBS	5.0	0.5	2g 85
7	1h	5.0	0.5	2h 92
8	1i	5.0	0.5	81 ^e 2i : R = OMe, R' = H, 2i' : R = H, R' = OMe (1.2:1) ^d
9	1j	7.5	1	2j 82

^a Reaction conditions: α -allenol **1** (0.50 mmol), LiPF₆, hexane (3.0 mL), 65 °C. ^b Yield is of isolated product. ^c In hexane/toluene (9:1). ^d Determined by ¹H NMR spectroscopy of the crude reaction mixture. ^e Combined yield of **2i** and **2i'**.

To further examine the substrate scope of this protocol, we focused on the cyclization of monosubstituted allenes. However, when **1k** was subjected to the standard reaction conditions, the expected product **2k** was hardly observed, and instead, enone **3** was obtained as a major product (Scheme 1).⁸ This result can be explained as follows: allenyl cation **A**, generated by C–O bond activation, is less stable due to the steric repulsion between the phenyl ring and the allenyl group. Therefore, rotation to another conformer **B** occurs, which is then attacked by LiOH to furnish enone **3**.

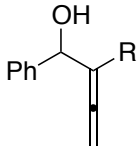
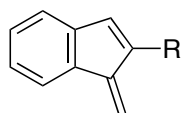
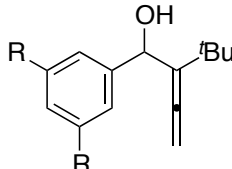
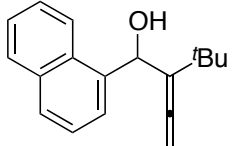
Scheme 1.

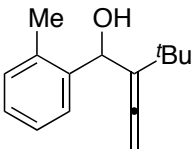
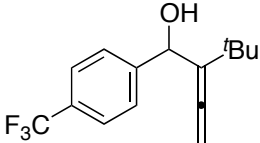
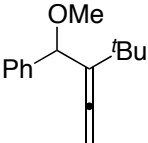


Remarkably, the present catalytic system has proved to be effective for Nazarov-type cyclization of *secondary* α -allenols, which has not been achieved thus far (Table 3). The author initially examined the effect of the substituent on the allene moiety. After some experimentation, the substituent on the allene moiety proved to be general (Table 3, entries 1–5). The best result was obtained when using *tert*-butyl substituted substrate **4e** (Table 3, entry 5). Electron-rich and electron-neutral substrates successfully underwent the cyclization to yield the corresponding

products in good yields (Table 3, entries 6 and 7). Sterically hindered aryl substituents such as, 1-naphthyl and *o*-tolyl did not inhibit the reaction at all (Table 3, entries 8 and 9). Electron-poor substrate gave moderate yield, although higher catalyst loading was required (Table 3, entry 10). In this transformation, not only α -allenol but also corresponding methyl ether could be used (Table 3, entry 11).

Table 3. Scope of Secondary α -Allenols^a

entry	substrate	[Li] (mol%)	product	yield (%) ^b
				
1	4a R = Me	5	5a	41
2	4b R = ⁿ Bu	15	5b	43
3	4c R = Ph	15	5c	42
4	4d R = TBS	20	5d	47
5	4e R = ^t Bu	15	5e	60
				
6	4f R = Me	20	5f	79
7	4g R = OMe	15	5g	80
8	4h 	15	5h	85

9	4i		15	5i	73
10	4j		30	5j	51
11	4k		15	5k	79

^a Reaction conditions: α -allenol **1** (0.50 mmol), LiPF₆, hexane (3.0 mL), 65 °C, 1 h. ^b Yield is of isolated product.

Conclusion

The author has clarified that lithium hexafluorophosphate proved to be effective for the C–O bond activation. He applied this strong oxophilic nature of LiPF₆ to the Nazarov-type cyclization of α -allenols. This process proceeds under mild conditions and can tolerate a variety of functional groups. Under the present catalytic system, *secondary* α -allenols could be also available as substrates, which has not been achieved thus far.

Experimental Section

Instrumentation

^1H NMR (500 MHz) and ^{13}C NMR (125.7 MHz) spectra were taken on a Varian UNITY INOVA 500 spectrometer. Chemical shifts (δ) are in parts per million relative to tetramethylsilane at 0.00 ppm for ^1H and relative to CDCl_3 at 77.23 ppm for ^{13}C unless otherwise noted. Mass spectra were determined on a JEOL Mstation 700 spectrometer. IR spectra were determined on a SHIMADZU IR Affinity-1 spectrometer. Melting points were determined using a YANAKO MP-500D. Kanto Chemical silica gel (spherical 40–100 μm) was used for column chromatography. Elemental analyses were carried out at the Elemental Analysis Center of Kyoto University.

Materials

LiPF_6 (H_2O 20 ppm max, 99.9+%-Li) was purchased from Strem Chemicals, Inc. NaPF_6 (98%) was purchased from Aldrich. KPF_6 (99.9+% trace metals basis) was purchased from Aldrich. NH_4PF_6 (99.99% trace metals basis) was purchased from Aldrich. HPF_6 (65 wt. % in H_2O) was purchased from Aldrich. Hexane (Super Dehydrated) was purchased from Wako Pure Chemical Co. α -Allenols **1** and **4** were prepared according to the known procedure.⁹ All other reagents were available from commercial sources and were used without further purification.

Experimental Procedures

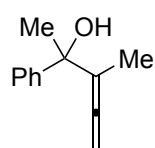
Representative Procedure for Lithium Cation-Catalyzed Nazarov-Type Cyclization of α -Allenols.

Compound 2a: In a glove box, lithium hexafluorophosphate (3.8 mg, 0.025 mmol) was placed in an oven-dried test tube equipped with a magnetic stirrer bar. Outside a glovebox, to the tube was added a solution of α -allenol **1a** (87.1 mg, 0.50 mmol) in hexane (3.0 mL). Then the

reaction mixture was heated at 65 °C for 1 h. After cooled to room temperature, the mixture was passed through a short activated alumina column with Et₂O and concentrated. The residue was purified by column chromatography on silica gel (hexane) to give **2a** (67.7 mg, 87%) as a yellow oil.

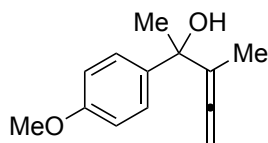
Characterization Data of New Compounds

3-Methyl-2-phenyl-3,4-pentadien-2-ol (**1a**):



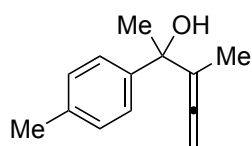
IR (neat) 3421, 2982, 1958, 1601, 1493, 1448, 1370 cm⁻¹; ¹H NMR (CDCl₃) δ 1.56 (dd, *J* = 3.0, 3.0 Hz, 3H), 1.66 (s, 3H), 2.04 (s, 1H), 4.86 (dq, *J* = 10.0, 3.0 Hz, 1H), 4.89 (dq, *J* = 10.0, 3.0 Hz, 1H), 7.22–7.26, (m, 1H), 7.31–7.35 (m, 2H), 7.44–7.48 (m, 2H); ¹³C NMR (CDCl₃) δ 14.84, 30.29, 75.17, 77.20, 106.08, 125.45, 127.05, 128.28, 146.20, 205.41. Found: C, 82.48; H, 8.24%. Calcd for C₁₂H₁₄O: C, 82.72; H, 8.10%.

2-(4-Methoxyphenyl)-3-methyl-3,4-pentadien-2-ol (**1b**):



IR (neat) 3461, 2981, 2835, 1957, 1610, 1584, 1511, 1443, 1299, 1249, 1176 cm⁻¹; ¹H NMR (CDCl₃) δ 1.56 (dd, *J* = 3.0, 3.0 Hz, 3H), 1.65 (s, 3H), 2.05 (s, 1H), 3.80 (s, 3H), 4.85 (dq, *J* = 10.0, 3.0 Hz, 1H), 4.87 (dq, *J* = 10.0, 3.0 Hz, 1H), 6.85–6.88, (m, 2H), 7.36–7.39 (m, 2H); ¹³C NMR (CDCl₃) δ 14.91, 30.16, 55.43, 74.81, 77.17, 106.27, 113.62, 126.69, 138.34, 158.70, 205.23. Found: C, 76.16; H, 8.19%. Calcd for C₁₃H₁₆O₂: C, 76.44; H, 7.90%.

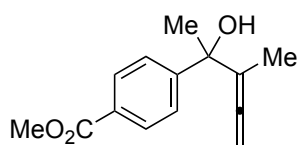
3-Methyl-2-(4-methylphenyl)-3,4-pentadien-2-ol (**1c**):



IR (neat) 3448, 2982, 2925, 1957, 1610, 1512, 1370, 1098 cm⁻¹; ¹H NMR (CDCl₃) δ 1.56 (dd, *J* = 3.0, 3.0 Hz, 3H), 1.65 (s, 3H), 2.03 (s, 1H), 2.34 (s, 3H), 4.85 (dq, *J* = 10.0, 3.0 Hz, 1H), 4.88 (dq, *J* = 10.0, 3.0 Hz, 1H), 7.12–7.16 (m, 2H), 7.32–7.36 (m, 2H); ¹³C NMR (CDCl₃) δ 14.88, 21.18, 30.25, 75.03, 77.15,

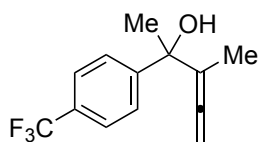
106.07, 125.36, 128.97, 136.62, 143.20, 205.30. Found: C, 82.83; H, 8.87%. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57%.

2-(4-Methoxycarbonyl)-3-methyl-3,4-pentadien-2-ol (1d):



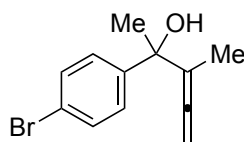
IR (neat) 3483, 2983, 2953, 1957, 1723, 1705, 1610, 1437, 1408, 1283, 1193 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.54 (dd, $J = 3.0, 3.0$ Hz, 3H), 1.67 (s, 3H), 2.09 (s, 1H), 3.91 (s, 3H), 4.88 (dq, $J = 10.0, 3.0$ Hz, 1H), 4.91 (dq, $J = 10.0, 3.0$ Hz, 1H), 7.52–7.55 (m, 2H), 7.99–8.02 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.68, 30.37, 52.22, 75.24, 77.48, 105.59, 125.57, 128.95, 129.65, 151.45, 167.19, 205.46. Found: C, 72.12; H, 6.98%. Calcd for $C_{14}H_{16}O_3$: C, 72.39; H, 6.94%.

3-Methyl-2-(4-trifluoromethylphenyl)-3,4-pentadien-2-ol (1e):

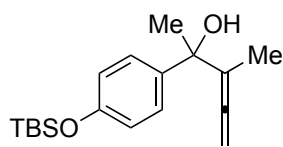


IR (neat) 3447, 2986, 2930, 1958, 1618, 1411, 1327, 1166, 1127, 1097, 1072 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.55 (dd, $J = 3.0, 3.0$ Hz, 3H), 1.66 (s, 3H), 2.07 (s, 1H), 4.88 (dq, $J = 10.0, 3.0$ Hz, 1H), 4.91 (dq, $J = 10.0, 3.0$ Hz, 1H), 7.58 (s, 4H); ^{13}C NMR (CDCl_3) δ 14.65, 30.48, 75.11, 77.53, 105.56, 124.46 (q, $J_{\text{C-F}} = 270.1$ Hz), 125.25 (q, $J_{\text{C-F}} = 3.9$ Hz), 125.93, 129.36 (q, $J_{\text{C-F}} = 32.5$ Hz), 150.30, 205.49. Found: C, 64.19; H, 5.39%. Calcd for $C_{13}H_{13}F_3O$: C, 64.46; H, 5.41%.

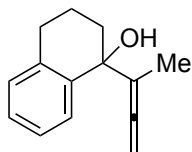
2-(4-Bromophenyl)-3-methyl-3,4-pentadien-2-ol (1f):



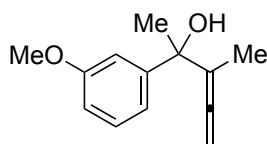
IR (neat) 3447, 2982, 2860, 1957, 1590, 1485, 1396, 1370, 1172 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.55 (dd, $J = 3.0, 3.0$ Hz, 3H), 1.63 (s, 3H), 2.01 (s, 1H), 4.86 (dq, $J = 10.0, 3.0$ Hz, 1H), 4.89 (dq, $J = 10.0, 3.0$ Hz, 1H), 7.31–7.35, (m, 2H), 7.43–7.46 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.71, 30.35, 74.95, 77.43, 105.69, 120.99, 127.42, 131.34, 145.33, 205.37. Found: C, 56.67; H, 5.23%. Calcd for $C_{12}H_{13}\text{BrO}$: C, 56.94; H, 5.18%.

2-(4-*tert*-Butyldimethylsiloxyphenyl)-3-methyl-3,4-pentadien-2-ol (1g):

IR (neat) 3433, 2957, 2859, 1958, 1608, 1507, 1263, 1257 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.19 (s, 6H), 0.98 (s, 9H), 1.55 (dd, $J = 3.0, 3.0$ Hz, 3H), 1.65 (s, 3H), 2.00 (s, 1H), 4.85 (dq, $J = 10.0, 3.0$ Hz, 1H), 4.87 (dq, $J = 10.0, 3.0$ Hz, 1H), 6.77–6.81 (m, 2H), 7.28–7.32 (m, 2H); ^{13}C NMR (CDCl_3) δ -4.23, 14.93, 18.38, 25.87, 29.99, 74.82, 77.20, 106.36, 119.69, 126.63, 138.79, 154.70, 205.12. Found: C, 70.96; H, 9.32%. Calcd for $\text{C}_{18}\text{H}_{28}\text{O}_2\text{Si}$: C, 71.00; H, 9.27%.

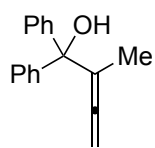
1-(2,3-Butadien-2-yl)-1,2,3,4-tetrahydronaphthalen-1-ol (1h):

IR (neat) 3442, 2937, 2865, 1957, 1604, 1488, 1373, 1077 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.59 (dd, $J = 3.0, 3.0$ Hz, 3H), 1.82–1.92 (m, 2H), 1.98–2.14 (m, 2H), 2.21 (s, 1H), 2.73 (ddd, $J = 16.0, 9.5, 5.5$ Hz, 1H), 2.82 (ddd, $J = 16.0, 4.5, 4.5$, 1H), 4.85 (dq, $J = 10.0, 3.0$ Hz, 1H), 4.91 (dq, $J = 10.0, 3.0$ Hz, 1H), 7.07–7.11 (m, 1H), 7.15–7.20 (m, 2H), 7.39–7.43 (m, 1H); ^{13}C NMR (CDCl_3) δ 15.84, 19.56, 29.95, 36.12, 73.10, 78.28, 107.08, 126.43, 127.64, 127.75, 129.13, 137.90, 139.49, 205.42. HRMS (EI^+) (m/z) Observed: 200.1194. Calcd for $\text{C}_{14}\text{H}_{16}\text{O}$: 200.1201.

2-(3-Methoxyphenyl)-3-methyl-3,4-pentadien-2-ol (1i):

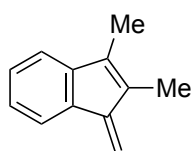
IR (neat) 3462, 2982, 2835, 1957, 1608, 1601, 1584, 1485, 1433, 1288, 1252 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.57 (dd, $J = 3.0, 3.0$ Hz, 3H), 1.65 (s, 3H), 2.02 (s, 1H), 3.82 (s, 3H), 4.86 (dq, $J = 10.0, 3.0$ Hz, 1H), 4.89 (dq, $J = 10.0, 3.0$ Hz, 1H), 6.79 (ddd, $J = 8.0, 2.5, 1.0$ Hz, 1H), 7.01–7.05 (m, 2H), 7.25 (dd, $J = 8.0, 8.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 14.82, 30.32, 55.40, 75.16, 77.20, 105.93, 111.61, 112.15, 117.93, 129.28, 148.02, 159.72, 205.40. Found: C, 76.49; H, 7.95%. Calcd for $\text{C}_{13}\text{H}_{16}\text{O}_2$: C, 76.44; H, 7.90%.

1,1-Diphenyl-2-methyl-2,3-butadien-1-ol (1j):



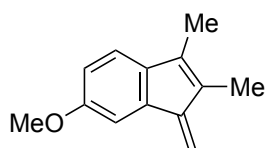
IR (neat) 3471, 3059, 2925, 1957, 1599, 1491, 1448, 1333 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.73 (t, $J = 3.0$ Hz, 3H), 2.67 (s, 1H), 4.68 (q, $J = 3.0$ Hz, 2H), 7.24–7.29 (m, 2H), 7.30–7.34 (m, 4H), 7.38–7.41 (m, 4H); ^{13}C NMR (CDCl_3) δ 16.55, 77.74, 80.84, 105.77, 127.48, 127.67, 128.00, 144.91, 206.60. HRMS (ESI) Calcd for $\text{C}_{17}\text{H}_{16}\text{O}$: m/z 237.1274 ($[\text{M}+\text{H}]^+$), found: 237.1267 ($[\text{M}+\text{H}]^+$).

2,3-Dimethyl-1-methylene-1H-indene (2a):



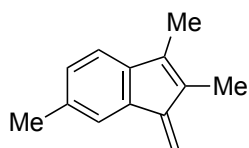
IR (neat) 3047, 2971, 1611, 1441, 1412 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.05–2.07 (m, 3H), 2.08–2.10 (m, 3H), 5.57 (s, 1H), 5.89 (s, 1H), 7.10–7.14 (m, 2H), 7.23 (ddd, $J = 7.5, 7.5, 1.0$ Hz, 1H), 7.48–7.52 (m, 1H); ^{13}C NMR (CDCl_3) δ 9.79, 10.68, 108.37, 117.74, 119.03, 124.76, 128.09, 131.95, 136.17, 137.27, 144.74, 148.70. HRMS (EI^+) (m/z) Observed: 156.0933. Calcd for $\text{C}_{12}\text{H}_{12}$: 156.0939.

2,3-Dimethyl-6-methoxy-1-methylene-1H-indene (2b):



IR (neat) 2913, 2832, 1610, 1586, 1477, 1435, 1382 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.01–2.03 (m, 3H), 2.04–2.06 (m, 3H), 3.83 (s, 3H), 5.52 (s, 1H), 5.83 (s, 1H), 6.76 (dd, $J = 8.0, 2.5$ Hz, 1H), 7.00 (d, $J = 8.0$ Hz, 1H), 7.11 (d, $J = 2.5$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 9.80, 10.76, 55.84, 106.73, 107.94, 112.40, 118.04, 130.35, 137.14, 137.96, 138.01, 148.67, 158.34. HRMS (EI^+) (m/z) Observed: 186.1042. Calcd for $\text{C}_{13}\text{H}_{14}\text{O}$: 186.1045.

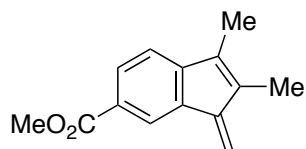
2,3,6-Trimethyl-1-methylene-1H-indene (2c):



IR (neat) 2915, 2856, 1632, 1613, 1475, 1440, 1381, 1344 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.01–2.03 (m, 3H), 2.04–2.06 (m, 3H), 3.83 (s, 3H), 5.52 (s, 1H), 5.83 (s, 1H), 6.76 (dd, $J = 8.0, 2.5$ Hz, 1H), 7.00 (d, $J = 8.0$ Hz, 1H), 7.11 (d, $J = 2.5$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 9.82, 10.77, 21.67, 107.96, 117.45, 120.08, 128.50, 131.11, 134.35, 136.37, 137.21, 142.20, 148.72. HRMS (EI^+) (m/z) Observed: 170.1096.

Calcd for $C_{13}H_{14}$: 170.1096.

2,3-Dimethyl-6-methoxycarbonyl-1-methylene-1*H*-indene (2d):

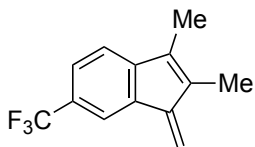


IR (nujol) 2955, 2893, 1726, 1707, 1603, 1463, 1254 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.09–2.10 (m, 3H), 2.10–2.11 (m, 3H), 3.92 (s, 3H), 5.68 (s, 1H), 6.01 (d, $J = 0.5$ Hz, 1H), 7.16 (d, $J = 7.5$ Hz, 1H), 7.97 (dd, $J =$

7.5, 1.5 Hz, 1H), 8.14 (dd, $J = 1.5, 0.5$ Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 10.06, 10.70, 52.09, 110.28, 117.39, 120.05, 126.49, 130.26, 135.75, 136.01, 137.09, 147.69, 149.05, 167.85.

Found: C, 78.54; H, 6.66%. Calcd for $C_{14}H_{14}O_2$: C, 78.48; H, 6.59%. m.p.: 86–89 °C.

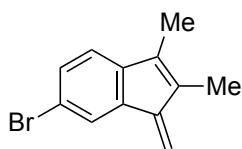
2,3-Dimethyl-1-methylene-6-trifluoromethyl-1*H*-indene (2e):



IR (neat) 2972, 2913, 2854, 1632, 1611, 1458, 1449, 1423, 1380 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.08 (s, 3H), 2.09 (s, 3H), 5.67 (s, 1H), 5.96 (d, $J = 0.5$ Hz, 1H), 7.16 (d, $J = 8.0$ Hz, 1H), 7.49 (dd, $J = 8.0, 1.0$ Hz, 1H), 7.68 (dd, $J =$

1.0, 1.0 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 9.93, 10.63, 110.40, 115.82 (q, $J_{C-F} = 3.9$ Hz), 117.57, 125.14 (q, $J_{C-F} = 270.1$ Hz), 125.34 (q, $J_{C-F} = 3.9$ Hz), 126.90 (q, $J_{C-F} = 32.0$ Hz), 134.96, 136.45, 136.77, 147.57, 147.80. HRMS (EI^+) (m/z) Observed: 224.0812. Calcd for $C_{13}H_{11}F_3$: 224.0813.

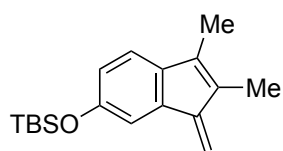
6-Bromo-2,3-dimethyl-1-methylene-1*H*-indene (2f):



IR (neat) 2929, 2854, 1611, 1458, 1423, 1380 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.02–2.04 (m, 3H), 2.05–2.07 (m, 3H), 5.61 (s, 1H), 5.87 (s, 1H), 6.96 (d, $J = 8.0$ Hz, 1H), 7.34 (dd, $J = 8.0, 2.0$ Hz, 1H), 7.58 (dd, $J = 2.0, 0.5$ Hz, 1H);

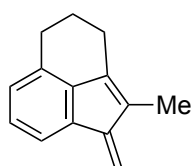
^{13}C NMR ($CDCl_3$) δ 9.85, 10.65, 109.77, 118.66, 119.01, 122.47, 130.65, 132.51, 136.85, 138.14, 143.52, 147.77. HRMS (EI^+) (m/z) Observed: 234.0037. Calcd for $C_{12}H_{11}Br$: 234.0044.

6-*tert*-Butyldimethylsiloxy-2,3-Dimethyl-1-methylene-1*H*-indene (2g)



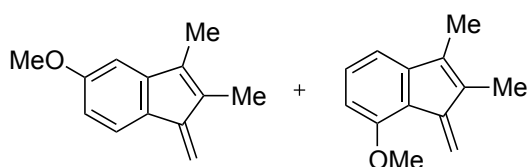
IR (neat) 2957, 2858, 1611, 1581, 1466, 1442, 1343, 1278 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.19 (s, 6H), 0.99 (s, 9H), 2.01–2.03 (m, 3H), 2.04–2.06 (m, 3H), 5.52 (s, 1H), 5.81 (s, 1H), 6.70 (dd, $J = 8.0, 2.0$ Hz, 1H), 6.94 (d, $J = 8.0$ Hz, 1H), 7.00 (d, $J = 2.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ -4.21, 9.84, 10.81, 18.41, 25.93, 108.09, 112.15, 118.02, 119.03, 130.43, 137.19, 137.76, 138.39, 148.59, 153.90. HRMS (EI^+) (m/z) Observed: 286.1756. Calcd for $\text{C}_{18}\text{H}_{26}\text{OSi}$: 286.1753.

1-(4-*tert*-Butyldimethylsiloxymethylphenyl)-4-phenylamino-1-butanone (2h):

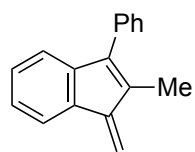


IR (nujol) 3040, 2835, 1816, 1806, 1626, 1593, 1472 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.92 (tt, $J = 6.0, 6.0$ Hz, 2H), 2.01 (t, $J = 1.0$ Hz, 3H), 2.59 (t, $J = 6.0$ Hz, 2H), 2.72 (t, $J = 6.0$ Hz, 2H), 5.57 (s, 1H), 5.87 (s, 1H), 6.96 (dd, $J = 7.0, 1.0$ Hz, 1H), 7.00 (dd, $J = 7.0, 7.0$ Hz, 1H), 7.29 (dd, $J = 7.0, 1.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 9.65, 23.47, 23.53, 27.23, 109.06, 117.18, 124.90, 126.61, 127.71, 131.00, 134.70, 138.32, 141.36, 149.74. Found: C, 92.01; H, 7.78%. Calcd for $\text{C}_{14}\text{H}_{14}$: C, 92.26; H, 7.74%. m.p.: 36–37 $^{\circ}\text{C}$.

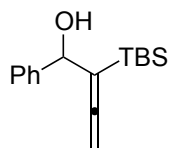
2,3-Dimethyl-5-methoxy-1-methylene-1*H*-indene/2,3-Dimethyl-7-methoxy-1-methylene-1*H*-indene (2i/2i'):



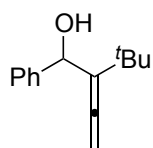
IR (neat) 2935, 2835, 1603, 1586, 1474, 1444, 1359, 1293 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.03–2.07 (m, 6H, **2i+2i'**), 3.83 (s, 3H, **2i**), 3.93 (s, 3H, **2i'**), 5.48 (s, 1H, **2i**), 5.70–5.72 (m, 1H, **2i'**), 5.75 (s, 1H, **2i**), 6.33–6.35 (m, 1H, **2i'**), 6.63 (dd, $J = 8.0, 2.5$ Hz, 1H, **2i**), 6.69 (d, $J = 2.5$ Hz, 1H, **2i**), 6.73 (d, $J = 8.5$ Hz, 1H, **2i'**), 6.81 (d, $J = 7.0$ Hz, 1H, **2i'**), 7.19 (dd, $J = 8.5, 7.0$ Hz, 1H, **2i'**), 7.39 (d, $J = 8.0$ Hz, 1H, **2i**); ^{13}C NMR (CDCl_3) δ 9.70, 9.97, 10.69, 10.82, 55.33, 55.65, 104.72, 107.04, 108.52, 108.93, 111.31, 113.81, 119.78, 121.32, 128.87, 128.97, 132.35, 133.36, 135.80, 136.58, 146.49, 146.83, 147.64, 148.01, 155.66, 160.52. HRMS (EI^+) (m/z) Observed: 186.1045. Calcd for $\text{C}_{13}\text{H}_{14}\text{O}$: 186.1045.

2-Methyl-1-methylene-3-phenyl-1H-indene (2j):

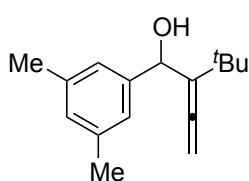
IR (neat) 3052, 2934, 2858, 1604, 1492, 1456, 1365 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.16 (s, 3H), 5.76 (s, 1H), 6.07 (s, 1H), 7.14–7.24 (m, 3H), 7.34–7.39 (m, 1H), 7.42–7.50 (m, 4H), 7.57–7.61 (m, 1H); ^{13}C NMR (CDCl_3) δ 10.69, 110.73, 119.28, 119.57, 125.08, 127.63, 128.16, 128.60, 129.18, 133.25, 135.14, 136.27, 141.62, 143.71, 148.89. HRMS (ESI) Calcd for $\text{C}_{17}\text{H}_{14}$: m/z 219.1168 ($[\text{M}+\text{H}]^+$), found: 219.1168 ($[\text{M}+\text{H}]^+$).

2-tert-Butyldimethylsilyl-1-phenyl-2,3-butadien-1-ol (4d):

IR (neat) 3421, 2955, 2928, 1927, 1603, 1493, 1463, 1362, 1249 cm^{-1} ; ^1H NMR (CDCl_3) δ -0.11 (s, 3H), 0.02 (s, 3H), 0.88 (s, 9H), 2.28 (s, 1H), 4.65 (dd, $J = 11.5$, 2.5 Hz, 1H), 4.69 (dd, $J = 11.5$, 3.0 Hz, 1H), 5.19 (dd, $J = 3.0$, 2.5 Hz, 1H), 7.24–7.29 (m, 1H), 7.30–7.38 (m, 4H); ^{13}C NMR (CDCl_3) δ -5.37, -5.27, 18.51, 26.89, 73.10, 73.49, 99.41, 127.28, 127.95, 128.45, 143.47, 209.08. HRMS (EI^+) (m/z) Observed: 260.1588. Calcd for $\text{C}_{16}\text{H}_{24}\text{OSi}$: 260.1596.

2-tert-Butyl-1-phenyl-2,3-butadien-1-ol (4e):

IR (neat) 3381, 2965, 1949, 1453, 1364, 1239 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.08 (s, 9H), 2.08 (s, 1H), 4.89 (dd, $J = 10.0$, 1.5 Hz, 1H), 4.99 (dd, $J = 10.0$, 1.5 Hz, 1H), 5.20–5.23 (m, 1H), 7.24–7.28 (m, 1H), 7.30–7.34 (m, 2H), 7.37–7.41 (m, 2H); ^{13}C NMR (CDCl_3) δ 30.01, 33.03, 71.00, 80.78, 117.73, 127.01, 127.75, 128.40, 143.85, 205.07. HRMS (EI^+) (m/z) Observed: 202.1355. Calcd for $\text{C}_{14}\text{H}_{18}\text{O}$: 202.1358.

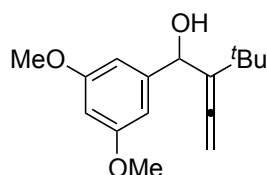
2-tert-Butyl-1-(3,5-dimethylphenyl)-2,3-butadien-1-ol (4f):

IR (neat) 3373, 2965, 1949, 1610, 1477, 1459, 1364, 1239 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.07 (s, 9H), 2.03 (d, $J = 6.0$ Hz, 1H), 2.31 (dd, $J = 0.5$, 0.5 Hz, 6H), 4.94 (dd, $J = 10.5$, 1.5 Hz, 1H), 5.01 (dd, $J = 10.5$, 2.0 Hz, 1H), 5.11–5.15 (m, 1H), 6.89–6.91 (m, 1H), 6.98–7.01 (m, 2H); ^{13}C NMR

(CDCl₃) δ 21.56, 30.05, 32.98, 70.97, 80.79, 117.58, 124.87, 129.47, 137.90, 143.71, 204.89.

Found: C, 83.41; H, 9.72%. Calcd for C₁₆H₂₂O: C, 83.43; H, 9.63%.

2-*tert*-Butyl-1-(3,5-dimethoxyphenyl)-2,3-butadien-1-ol (4g):



IR (neat) 3432, 2964, 2837, 1948, 1609, 1598, 1463, 1429 cm⁻¹; ¹H

NMR (CDCl₃) δ 1.09 (s, 9H), 2.08 (d, J = 7.0 Hz, 1H), 3.79 (s, 6H), 4.92

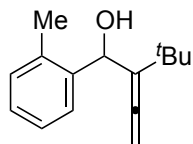
(dd, J = 10.5, 1.5 Hz, 1H), 5.00 (dd, J = 10.5, 1.5 Hz, 1H), 5.11–5.15 (m,

1H), 6.37 (t, J = 2.5 Hz, 1H), 6.57 (dd, J = 2.5, 0.5 Hz, 2H); ¹³C NMR (CDCl₃) δ 29.97, 33.03,

55.48, 71.05, 80.82, 99.49, 105.16, 117.44, 146.35, 160.78, 205.06. Found: C, 73.34; H, 8.56%.

Calcd for C₁₆H₂₂O₃: C, 73.25; H, 8.45%.

2-*tert*-Butyl-1-(2-methylphenyl)-2,3-butadien-1-ol (4i):



IR (neat) 3337, 2966, 1948, 1461, 1363 cm⁻¹; ¹H NMR (CDCl₃) δ 1.08 (s, 9H),

1.95 (br s, 1H), 2.39 (s, 3H), 4.82 (dd, J = 10.5, 2.5 Hz, 1H), 4.90 (dd, J = 10.5,

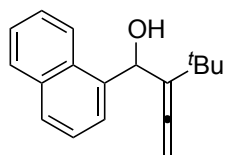
2.5 Hz, 1H), 5.45 (dd, J = 2.5, 2.5 Hz, 1H), 7.12–7.21 (m, 3H), 7.42–7.46 (m,

1H); ¹³C NMR (CDCl₃) δ 19.42, 30.34, 33.03, 68.07, 80.13, 116.27, 125.98, 126.56, 127.68,

130.63, 135.66, 141.33, 205.37. HRMS (EI⁺) (m/z) Observed: 216.1517. Calcd for C₁₅H₂₀O:

216.1514.

2-*tert*-Butyl-1-(1-naphthyl)-2,3-butadien-1-ol (4j):



IR (neat) 3335, 3051, 2964, 1948, 1598, 1511, 1394, 1363 cm⁻¹; ¹H NMR

(CDCl₃) δ 1.12 (s, 9H), 2.12 (br s, 1H), 4.80 (dd, J = 10.5, 2.5 Hz, 1H), 4.92

(dd, J = 10.5, 2.5 Hz, 1H), 6.01 (dd, J = 2.5, 2.5 Hz, 1H), 7.45 (dd, J = 8.0,

7.0 Hz, 1H), 7.48 (ddd, J = 8.0, 7.0, 1.0 Hz, 1H), 7.54 (ddd, J = 8.0, 6.5, 1.5 Hz, 1H), 7.66 (dd, J

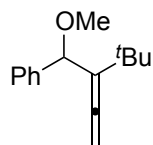
= 7.0, 1.0 Hz, 1H), 7.79 (d, J = 8.5 Hz, 1H), 7.85–7.88 (m, 1H), 8.22 (d, J = 0.5 Hz, 1H); ¹³C

NMR (CDCl₃) δ 30.31, 33.21, 67.99, 80.44, 116.42, 123.76, 124.66, 125.29, 125.68, 126.31,

128.65, 128.92, 131.40, 134.12, 138.73, 205.73. HRMS (EI⁺) (m/z) Observed: 252.1508.

Calcd for C₁₈H₂₀O: 252.1514.

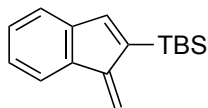
2-*tert*-Butyl-1-methoxy-1-phenyl-2,3-butadiene (4k):



IR (neat) 2966, 2818, 1951, 1453, 1363 cm⁻¹; ¹H NMR (CDCl₃) δ 1.10 (s, 9H), 3.29 (s, 3H), 4.68–4.72 (m, 2H), 4.83 (dd, *J* = 11.0, 2.0 Hz, 1H), 7.23–7.27 (m, 1H), 7.30–7.36 (m, 4H); ¹³C NMR (CDCl₃) δ 29.94, 33.05, 57.02, 78.95, 81.08, 114.64,

127.50, 127.59, 128.16, 141.50, 206.80. HRMS (ESI) Calcd for C₁₅H₂₀O: *m/z* 217.1587 ([M+H]⁺), found: 217.1581 ([M+H]⁺).

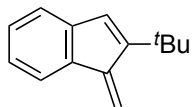
2-*tert*-Butyldimethylsilyl-1-methylene-1*H*-indene (5d):



IR (neat) 3067, 2955, 2884, 1602, 1506, 1409 cm⁻¹; ¹H NMR (CDCl₃) δ 0.29 (s, 6H), 0.93 (s, 9H), 5.82 (s, 1H), 6.19 (d, *J* = 2.0 Hz, 1H), 7.14–7.16 (m, 1H), 7.19 (ddd, *J* = 7.0, 7.0, 1.5 Hz, 1H), 7.25 (ddd, *J* = 7.0, 7.0, 1.0 Hz, 1H), 7.26–7.29 (m, 1H), 7.60 (ddd, *J* = 7.0, 1.5, 0.5 Hz, 1H); ¹³C NMR (CDCl₃) δ -4.31, 17.08, 27.06, 115.68, 119.62,

120.56, 125.68, 128.13, 139.35, 139.42, 143.49. HRMS (EI⁺) (*m/z*) Observed: 242.1483. Calcd for C₁₆H₂₂Si: 242.1491.

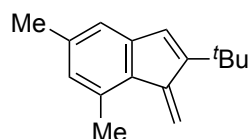
2-*tert*-Butyl-1-methylene-1*H*-indene (5e):



IR (neat) 3069, 2964, 2869, 1626, 1606, 1462, 1363 cm⁻¹; ¹H NMR (CDCl₃) δ 1.36 (s, 9H), 5.94 (s, 1H), 6.17 (d, *J* = 1.0 Hz, 1H), 6.59–6.61 (m, 1H), 7.08–7.20 (m, 3H), 7.47–7.50 (m, 1H); ¹³C NMR (CDCl₃) δ 31.53, 33.43, 113.84, 119.11,

120.11, 124.79, 128.21, 128.52, 137.92, 141.74, 145.90, 151.06. HRMS (EI⁺) (*m/z*) Observed: 184.1254. Calcd for C₁₄H₁₆: 184.1252.

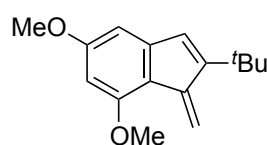
2-*tert*-Butyl-5,7-dimethyl-1-methylene-1*H*-indene (5f):



IR (nujol) 2953, 2867, 1616, 1585, 1479, 1363 cm⁻¹; ¹H NMR (CDCl₃) δ 1.37 (s, 9H), 2.31 (s, 3H), 2.48 (s, 3H), 6.06 (s, 1H), 6.14 (d, *J* = 1.5 Hz,

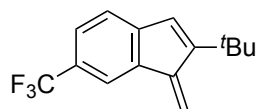
1H), 6.52 (d, $J = 1.0$ Hz, 1H), 6.72 (dd, $J = 1.5, 1.0$ Hz, 1H), 6.86 (s, 1H); ^{13}C NMR (CDCl_3) δ 21.17, 21.48, 31.67, 33.35, 117.45, 119.37, 127.84, 129.30, 131.49, 132.97, 137.56, 142.74, 147.48, 151.45. Calcd for $\text{C}_{16}\text{H}_{20}$: 212.1565. Found: C, 90.27; H, 9.63%. Calcd for $\text{C}_{16}\text{H}_{20}$: C, 90.51; H, 9.49%. m.p.: 39–42 °C.

2-*tert*-Butyl-5,7-dimethoxyl-1-methylene-1*H*-indene (5g):



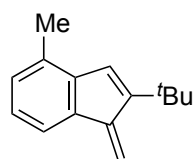
IR (nujol) 2953, 1592, 1507, 1359, 1314, 1258, 1211, 1154 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.36 (s, 9H), 3.82 (s, 3H), 3.90 (s, 3H), 6.01 (d, $J = 0.5$ Hz, 1H), 6.29 (d, $J = 2.0$ Hz, 1H), 6.42 (d, $J = 2.0$ Hz, 1H), 6.46 (d, $J = 1.0$ Hz, 1H), 6.58 (dd, $J = 1.0, 1.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 31.70, 33.49, 55.29, 55.73, 95.66, 98.76, 116.10, 117.77, 127.06, 144.64, 144.93, 152.64, 156.87, 161.35. Found: C, 78.63; H, 8.49%. Calcd for $\text{C}_{16}\text{H}_{20}\text{O}_2$: C, 78.65; H, 8.25%. m.p.: 75–77 °C.

2-*tert*-Butyl-6-trifluoromethyl-1-methylene-1*H*-indene (5h):



IR (nujol) 2869, 1852, 1618, 1549, 1443, 1326, 1310, 1271 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.38 (s, 9H), 6.08 (s, 1H), 6.28 (d, $J = 1.5$ Hz, 1H), 6.64–6.66 (m, 1H), 7.23 (d, $J = 7.5$ Hz, 1H), 7.46 (dd, $J = 7.5, 1.0$ Hz, 1H), 7.70 (d, $J = 1.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 31.44, 33.65, 115.94, 115.98, 116.0 (q, $J_{\text{C-F}} = 3.8$ Hz), 119.96, 125.0 (q, $J_{\text{C-F}} = 270.1$ Hz), 125.31 (q, $J_{\text{C-F}} = 4.0$ Hz), 126.8 (q, $J_{\text{C-F}} = 31.5$ Hz), 127.81, 138.08, 144.79, 153.97. HRMS (EI^+) (m/z) Observed: 252.1129. Calcd for $\text{C}_{15}\text{H}_{15}\text{F}_3$: 252.1126. m.p.: 37–38 °C.

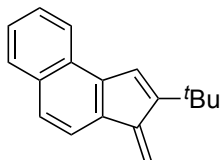
2-*tert*-Butyl-4-methyl-1-methylene-1*H*-indene (5i):



IR (nujol) 2856, 1836, 1599, 1546, 1363, 1246 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.37 (s, 9H), 2.36 (s, 3H), 5.94 (s, 1H), 6.17 (d, $J = 1.5$ Hz, 1H), 6.67–6.69 (m, 1H), 6.99–7.04 (m, 2H), 7.33–7.36 (m, 1H); ^{13}C NMR (CDCl_3) δ 18.18, 31.58, 33.47, 114.03, 116.70, 124.88, 129.29, 129.44, 137.69, 140.22, 146.18, 150.34. HRMS (EI^+)

(*m/z*) Observed: 198.1411. Calcd for C₁₅H₁₈: 198.1409. m.p.: 66–67 °C.

2-*tert*-Butyl-3-methylene-3*H*-cyclopenta[*a*]naphthalene (5j):



IR (nujol) 2868, 1842, 1625, 1517, 1361 cm⁻¹; ¹H NMR (CDCl₃) δ 1.44 (s, 9H), 6.16 (s, 1H), 6.36 (d, *J* = 1.0 Hz, 1H), 7.13–7.15 (m, 1H), 7.40 (ddd, *J* = 8.0, 6.5, 1.0 Hz, 1H), 7.46 (ddd, *J* = 8.0, 7.0, 1.5 Hz, 1H), 7.62 (d, *J* = 8.5 Hz, 1H), 7.66 (d, *J* = 8.5 Hz, 1H), 7.80–7.84 (m, 1H), 8.00–8.03 (m, 1H); ¹³C NMR (CDCl₃) δ 31.94, 33.67, 116.54, 118.02, 123.93, 124.66, 125.45, 125.52, 125.87, 127.10, 128.67, 133.95, 134.17, 137.99, 146.87, 150.32. HRMS (ESI) Calcd for C₁₈H₁₈: *m/z* 235.1481 ([M+H]⁺), found: 235.1476 ([M+H]⁺). m.p.: 77–79 °C.

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Chapter 4

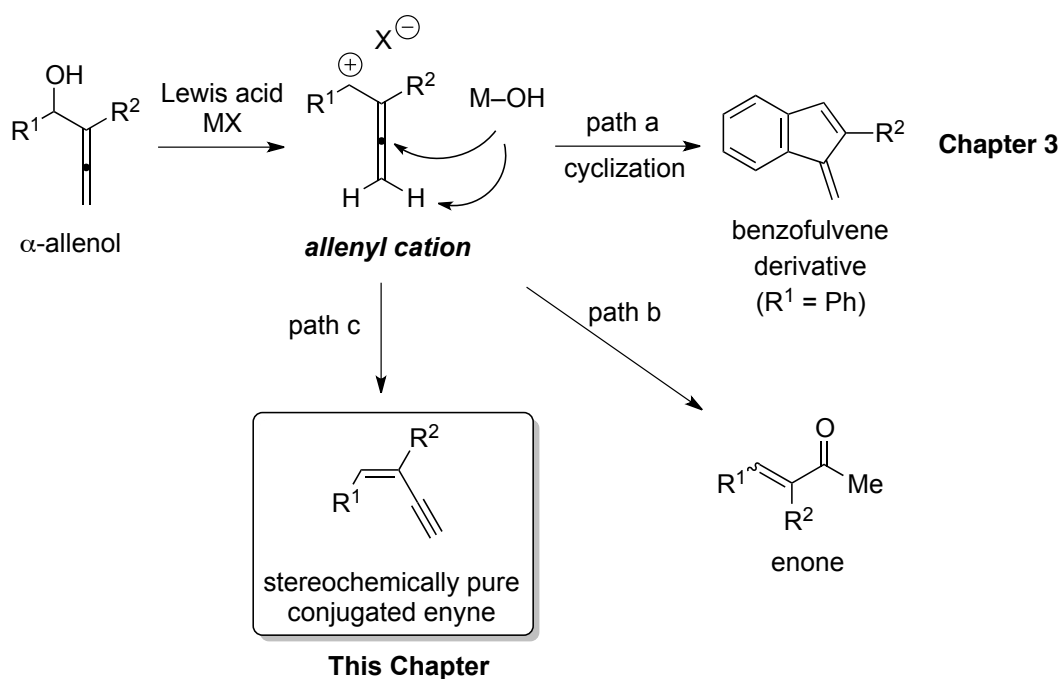
Copper-Catalyzed Stereoselective Synthesis of Functionalized Conjugated Enynes, Dienynes, and Eneidyne from α -Allenols

Treatment of TIPS-substituted α -allenols in the presence of a catalytic amount of copper(II) triflate affords the corresponding conjugated enynes with complete *E*-selectivity. This process can tolerate a wide variety of functional groups. This method can be also applied to the synthesis of conjugated dienynes and eneidyne.

Introduction

Conjugated enynes are important structures that serve as key components of a wide range of biologically active compounds, natural products, pharmaceuticals, and functional organic materials.¹ Due to the importance of this structural unit, many synthetic approaches have been developed. The most common and straightforward method is the Pd/Cu co-catalyzed cross-coupling of an alkenyl halide with a terminal alkyne, known as the Sonogashira reaction.² Recently, less expensive metal-based variants using Cu, Co, Ni, and Fe as a single catalyst have been intensively studied, which often accommodate substrates that are difficult to employ by the Pd-based protocols.³ However, despite the great synthetic utility of the coupling approach, the stereocontrolled synthesis of functionalized conjugated enynes is somewhat difficult for some reason: (1) the coupling reaction generally proceeds with retention of stereochemistry of starting alkenyl halides, requiring the use of stereochemically pure starting materials, which can be challenging to access, (2) the partial loss of the stereochemical information of alkenyl halides occurs in some cases, (3) functional groups such as carbon–halogen bonds are not compatible under low valent metal catalysis. As such, the development of a more practical method for the stereocontrolled synthesis of functionalized conjugated enynes remains an ongoing synthetic challenge. In Chapter 3, the author reported a Li⁺-catalyzed Nazarov-type cyclization reaction of 1-aryl-2,3-butadien-1-ols. This reaction proceeds via formation of the allenyl cation intermediate by C–O bond activation, which undergoes Nazarov-type cyclization to give benzofulvene derivative (Scheme 1, path a). In this transformation, enones are frequently obtained as major byproducts, presumably via S_N2'-type attack of metal hydroxide on the allenyl center (Scheme 1, path b). Therefore, we reasoned that if the metal hydroxide selectively abstracts the allenyl proton instead of attacking the allenyl center (Scheme 1, path c), an efficient and practical method for the synthesis of functionalized conjugated enynes would be realized. In Chapter 4, the author reports a copper-catalyzed stereoselective synthesis of functionalized conjugated enynes, dienynes, and enediynes from α -allenols.

Scheme 1.



Results and Discussion

Initially, we examined the transformation of α -allenol **1a**⁴ using various catalysts (Table 1). While the use of LiPF_6 did afford the desired enyne **2a**, the yield was only 14% and no stereoselectivity was observed (Table 1, entry 1). In addition, as predicted, significant amounts of benzofulvene **3a** and enone **4a** were also formed. Other representative Lewis acid such as FeCl_3 , InCl_3 , and $\text{Yb}(\text{OTf})_3$ resulted in poor conversion (Table 1, entries 2–4); in the case of FeCl_3 and InCl_3 , 2-chloro-1,3-butadiene **6a** was formed by an $\text{S}_{\text{N}}2'$ -type attack of chloride on the allenyl center.⁵ $\text{Sc}(\text{OTf})_3$ improved the yield of **2a** to 50%, but byproducts **3a** and **4a** were still detected (Table 1, entry 5). The use of AgOTf led to the formation of 2,5-dihydrofuran **5a** as the major product derived from oxycyclization⁶ (Table 1, entry 6). Further investigations revealed that copper salts were uniquely effective for the current reaction and copper(II) triflate proved to be the optimal catalyst, affording **2a** in 83% yield (Table 1, entry 8).

Table 1. Optimization of Reaction Conditions

entry	catalyst	yield (%) ^a				
		2a (<i>E/Z</i>) ^a	1a	3a	4a	5a
1	LiPF ₆	14 (1:1)	0	17	33	0
2 ^b	FeCl ₃	<1	70	4	2	0
3 ^b	InCl ₃	<1	78	3	1	0
4	Yb(OTf) ₃	13 (1:1.1)	76	3	3	0
5	Sc(OTf) ₃	50 (1.8:1)	0	26	22	0
6	AgOTf	22 (1:1.1)	31	1	5	35
7	CuOTf · 0.5C ₆ H ₆	69 (1.3:1)	0	9	16	7
8	Cu(OTf) ₂	83 (1.4:1)	0	5	11	0

^a Determined by ¹H NMR spectroscopy of the crude reaction mixture. ^b 2-Chloro-1,3-butadiene **6a** was detected as the major product.

In order to improve the stereoselectivity of this process, we next evaluated the influence of the substituents R on the allene moiety (Table 2). Although replacing the *n*-butyl group of **1a** with phenyl group did not improve the selectivity at all (Table 2, entry 1), switching to more sterically demanding substituents such as silyl groups led to the complete *E*-selectivity (Table 2, entries 2–4). Comparable results were also observed when using *tert*-butyl group containing substrate (Table 2, entry 5), showing that the stereoselectivity is simply controlled by sterics in this system. Finally, the best result was obtained with TIPS containing substrate **7a**, affording

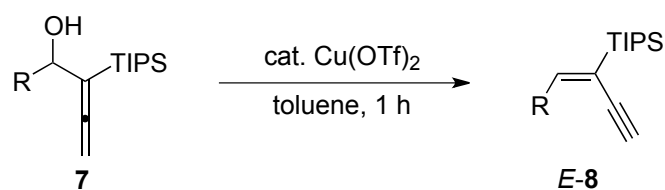
the *E*-enyne **8a** in 82% isolated yield (Table 2, entry 4).

Table 2. Effects of the Substituents R on the Allene Moiety

entry	R	Cu (mol%) /T (°C)	yield (%) ^a	<i>E/Z</i> ^a
1	Ph	5.0/85	49	55/45
2	TMS	5.0/75	69	<i>E</i> only
3	TBS	5.0/75	64	<i>E</i> only
4	TIPS 7a	5.0/75	8a 83 (82) ^b	<i>E</i> only
5	^t Bu	5.0/75	78	<i>E</i> only

^a Determined by ¹H NMR spectroscopy of the crude reaction mixture. ^b Isolated yield.

Having established the optimal conditions, we explored the scope of the reaction. A variety of TIPS-substituted α -allenols can be transformed into the corresponding *E*-enynes in good to excellent yields (Table 3). α -Allenols bearing electron-donating units work especially well (Table 3, entries 1 and 2). The use of substrate containing a strong electron-withdrawing group gives somewhat lower yield (Table 3, entry 3 and 4). Aryl halides including iodides are well tolerated under the reaction conditions, which represents an advantage of this method when comparing with the classical protocols involving low valent metal catalysis (Table 3, entries 5–7). Steric hindrance around the hydroxy functionality does not affect the reaction efficacy (Table 3, entry 8). The reaction allows the use of vinyl-substituted substrate (Table 3, entry 9). S-containing heterocyclic substrate also readily undergoes the transformation (Table 3, entry 10). Importantly, in all cases, none of the *Z*-isomers could be detected by ¹H NMR analysis of the crude reaction mixtures.⁷

Table 3. Copper-Catalyzed Stereoselective Synthesis of TIPS-Substituted Conjugated *E*-Enynes

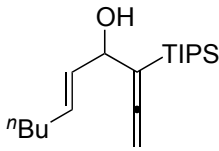
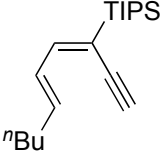
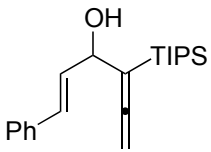
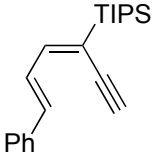
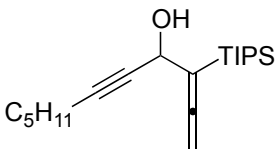
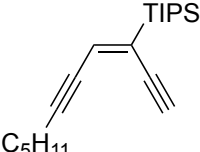
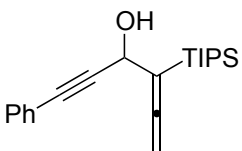
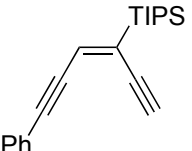
entry	R		Cu (mol%) /T (°C)	product	yield (%) ^a
1	4-MeO-C ₆ H ₄	7b	1.0/60	<i>E</i> - 8b	96
2	4-TBSO-C ₆ H ₄	7c	1.0/60	<i>E</i> - 8c	92
3	4-F-C ₆ H ₄	7d	5.0/85	<i>E</i> - 8d	86
4	4-EtO ₂ C-C ₆ H ₄	7e	5.0/85	<i>E</i> - 8e	46
5	4-Cl-C ₆ H ₄	7f	5.0/85	<i>E</i> - 8f	86
6	4-Br-C ₆ H ₄	7g	5.0/85	<i>E</i> - 8g	85
7	4-I-C ₆ H ₄	7h	6.0/85	<i>E</i> - 8h	86
8	2,6-Me ₂ -C ₆ H ₃	7i	5.0/85	<i>E</i> - 8i	90
9 ^b	4-CH ₂ =CH-C ₆ H ₄	7j	5.0/80	<i>E</i> - 8j	87
10	2-thienyl	7k	1.0/60	<i>E</i> - 8k	91

^a Yield is of isolated product. ^b For 0.5 h.

Encouraged by these results, we next applied this catalytic system to the synthesis of conjugated dienynes and enediynes. In particular, conjugated enediynes are most known for their potent antitumor activity that cleaves DNA by generating reactive diradicals via the Bergman cyclization.⁸ Gratifyingly, the reaction of α -allenols bearing an alkyl- and aryl-substituted alkene moiety works well to yield the corresponding *E,E*-dienynes as the sole product (Table 4, entries 1 and 2). We also examined the reaction of α -allenol **9c** having an alkyl-substituted alkyne moiety (Table 4, entry 3). While this reaction exhibited high

stereoselectivity in favor of the *E*-isomer (*E/Z* = 92:8), the complete *E*-selectivity could not be achieved. This is likely due to the linear geometry of an alkyne, which decreases the steric repulsion between the alkynyl substituent and the bulky silyl group that exists in the *Z*-isomer; as a result, small amount of the *Z*-isomer is formed. Similar results were observed when using other alkyne containing substrates (Table 4, entry 4). It should be noted that *E/Z* isomers of **10** can be readily separated by column chromatography as they have different R_f value.⁹

Table 4. Copper-Catalyzed Stereoselective Synthesis of TIPS-Substituted Conjugated *E,E*-Dienynes and *E*-Enediynes

entry	substrate	Cu (mol%) /T (°C)	product	yield (%) ^a (<i>E/Z</i>) ^b
1	 9a	1.0/60	 <i>E,E</i>-10a	69
2	 9b	1.0/60	 <i>E,E</i>-10b	85
3 ^c	 9c	2.5/85	 <i>E</i>-10c	70 (92:8)
4 ^c	 9d	2.5/85	 <i>E</i>-10d	73 (91:9)

^a Yield is of isolated *E,E*- or *E*-**10**. ^b Determined by ¹H NMR spectroscopy of the crude reaction

mixture.^c For 0.5 h.

To gain information about the high *E*-stereoselectivity of this process, we examined the possibility of olefin isomerization under the reaction conditions. Treatment of *Z*-**10d** with a copper catalyst at 60 °C resulted in no formation of *E*-**10d** (Table 5, entry 1). However, at 75 °C, the isomerization was observed with *E*-**10d** becoming detectable (Table 5, entry 2). Heating of *Z*-**10d** at 85 °C led to the complete reversal of product stereochemistry, and the *Z*/*E* ratio was 9:91 (Table 5, entry 3). The use of higher catalyst loading did not further improve the stereoselectivity; the *Z*/*E* ratio was again 9:91 (Table 5, entry 4). These results indicate that an equilibrium between *Z*- and *E*-**10d** is taking place under the reaction conditions, and thermodynamically more stable *E*-**10d** is predominantly formed at high temperature. It should be noted that the isomerization did not proceed in the absence of a copper catalyst even at 85 °C (Table 5, entry 5).

Table 5. Copper-Catalyzed Isomerization of *Z*-**10d** to *E*-**10d**

Z-10d $\xrightarrow[\text{toluene, 0.5 h}]{\text{cat. Cu(OTf)}_2}$ **E-10d**

entry	Cu (mol%)	T (°C)	<i>Z</i> - 10d / <i>E</i> - 10d
1	2.5	60	100:0
2	2.5	75	80:20
3	2.5	85	9:91
4	5.0	85	9:91
5	—	85	100:0

Conclusion

The author has developed a copper-catalyzed stereoselective synthesis of conjugated enynes from α -allenols. This process proceeds with complete *E*-selectivity and can tolerate a variety of functional groups such as ether, siloxy, halogen, trifluoromethyl, vinyl, and heteroaryl groups. The author has also applied this method to the synthesis of conjugated dienynes and enediynes.

Experimental Section

Instrumentation

^1H NMR (500 MHz) and ^{13}C NMR (125.7 MHz) spectra were taken on a Varian UNITY INOVA 500 spectrometer. Chemical shifts (δ) are in parts per million relative to tetramethylsilane at 0.00 ppm for ^1H and relative to CDCl_3 at 77.23 ppm for ^{13}C unless otherwise noted. Mass spectra were determined on a JEOL Mstation 700 spectrometer. IR spectra were determined on a SHIMADZU IR Affinity-1 spectrometer. Melting points were determined using a YANAKO MP-500D. Kanto Chemical silica gel (spherical 40–100 μm) was used for column chromatography. Elemental analyses were carried out at the Elemental Analysis Center of Kyoto University.

Materials

Materials were obtained from commercial suppliers and purified by the standard procedures unless otherwise noted. Copper(II) triflate was purchased from Wako Chemical Co. Toluene (super dehydrated) was purchased from Wako Pure Chemical Co. α -Allenols were prepared according to the known procedure.⁴

Experimental Procedures

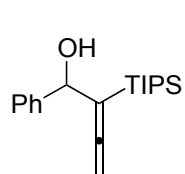
Representative Procedure for Copper-Catalyzed Stereoselective Synthesis of *E*-Enynes from α -Allenols.

Compound 8a: copper(II) triflate (9.0 mg, 5.0 mol%) was placed in an oven-dried test tube with a magnetic stirrer bar. The tube was filled with argon and sealed with a rubber septum. To the tube was added a solution of α -allenol **7a** (151.3 mg, 0.50 mmol) in toluene (3.0 mL). Then the reaction mixture was heated at 75 $^\circ\text{C}$ for 1 h. After cooled to room temperature, the mixture

was passed through a short activated alumina column with Et₂O and concentrated. The residue was purified by column chromatography (hexane) to give **8a** (116.4 mg, 82%).

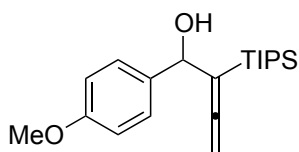
Characterization Data of New Compounds

1-Phenyl-2-triisopropylsilyl-2,3-butadien-1-ol (**7a**):



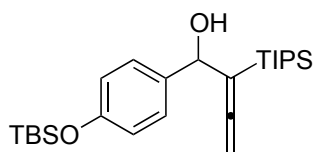
IR (neat) 3447, 2944, 2889, 1925, 1464, 1383 cm⁻¹; ¹H NMR (CDCl₃) δ 0.94 (d, *J* = 7.5 Hz, 9H), 1.07 (d, *J* = 7.5 Hz, 9H), 1.12–1.20 (m, 3H), 2.27 (br s, 1H), 4.62 (dd, *J* = 11.5, 2.5 Hz, 1H), 4.68 (dd, *J* = 11.5, 2.5 Hz, 1H), 5.16 (dd, *J* = 2.5, 2.5 Hz, 1H), 7.25–7.29 (m, 1H), 7.31–7.35 (m, 2H), 7.38–7.41 (m, 2H); ¹³C NMR (CDCl₃) δ 11.87, 18.56, 18.78, 72.63, 73.43, 97.49, 127.36, 127.97, 128.43, 143.52, 209.80. HRMS (APCI) calcd for C₁₉H₃₁OSi [M+H]⁺: 303.2139. Found: 303.2136.

1-(4-Methoxyphenyl)-2-triisopropylsilyl-2,3-butadien-1-ol (**7b**):



IR (nujol) 3443, 2902, 1922, 1610, 1511 cm⁻¹; ¹H NMR (CDCl₃) δ 0.94 (d, *J* = 7.5 Hz, 9H), 1.06 (d, *J* = 7.0 Hz, 9H), 1.11–1.19 (m, 3H), 2.22 (d, *J* = 5.5 Hz, 1H), 3.80 (s, 3H), 4.64 (dd, *J* = 11.5, 2.0 Hz, 1H), 4.70 (dd, *J* = 11.5, 2.5 Hz, 1H), 5.11 (ddd, *J* = 5.5, 2.5, 2.5 Hz, 1H), 6.84–6.88 (m, 2H), 7.30–7.34 (m, 2H); ¹³C NMR (CDCl₃) δ 11.85, 18.57, 18.80, 55.44, 72.05, 73.47, 97.61, 113.76, 128.69, 135.78, 159.37, 209.56. HRMS (APCI) calcd for C₂₀H₃₂O₂Si [M+H]⁺: 333.2244. Found: 333.2241.

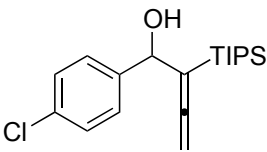
1-(4-*tert*-Butyldimethylsiloxyphenyl)-2-triisopropylsilyl-2,3-butadien-1-ol (**7c**):



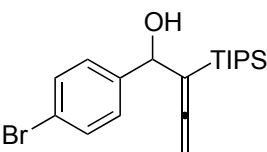
IR (neat) 3442, 2944, 2864, 1925, 1608, 1507, 1464 cm⁻¹; ¹H NMR (CDCl₃) δ 0.17 (s, 6H), 0.92 (d, *J* = 7.0 Hz, 9H), 0.97 (s, 9H), 1.05 (d, *J* = 7.0 Hz, 9H), 1.08–1.17 (m, 3H), 2.26 (d, *J* = 6.0 Hz, 1H), 4.66 (dd, *J* = 11.0, 2.5 Hz, 1H), 4.71 (dd, *J* = 11.0, 2.5 Hz, 1H), 5.09 (ddd, *J* = 6.0, 2.5, 2.5 Hz, 1H),

6.78–6.81 (m, 2H), 7.24–7.27 (m, 2H); ^{13}C NMR (CDCl_3) δ -4.27, 11.84, 18.43, 18.54, 18.79, 25.88, 72.07, 73.57, 97.75, 120.19, 128.68, 136.38, 155.53, 209.26. HRMS (APCI) calcd for $\text{C}_{25}\text{H}_{44}\text{O}_2\text{Si}_2\text{Cl}$ $[\text{M}+\text{Cl}]^-$: 467.2563. Found: 467.2562.

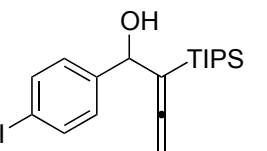
1-(4-Chlorophenyl)-2-triisopropylsilyl-2,3-butadien-1-ol (7e):

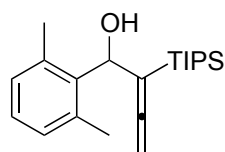
 IR (neat) 3446, 2944, 2866, 1925, 1596, 1490, 1464 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.97 (d, $J = 7.0$ Hz, 9H), 1.07 (d, $J = 7.5$ Hz, 9H), 1.12–1.21 (m, 3H), 2.23 (d, $J = 6.0$ Hz, 1H), 4.60 (dd, $J = 11.5$, 2.0 Hz, 1H), 4.65 (dd, $J = 11.5$, 2.5 Hz, 1H), 5.14 (ddd, $J = 6.0$, 2.5, 2.0 Hz, 1H), 7.28–7.34 (m, 4H); ^{13}C NMR (CDCl_3) δ 11.85, 18.62, 18.77, 72.02, 73.56, 97.38, 128.53, 128.65, 133.53, 142.10, 210.06. HRMS (APCI) calcd for $\text{C}_{19}\text{H}_{30}\text{ClOSi}$ $[\text{M}+\text{H}]^+$: 337.1749. Found: 337.1741.

1-(4-Bromophenyl)-2-triisopropylsilyl-2,3-butadien-1-ol (7f):

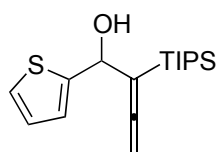
 IR (neat) 3429, 2944, 2865, 1924, 1591, 1486, 1464 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.97 (d, $J = 7.5$ Hz, 9H), 1.07 (d, $J = 7.5$ Hz, 9H), 1.13–1.21 (m, 3H), 2.23 (d, $J = 6.0$ Hz, 1H), 4.59 (dd, $J = 11.5$, 2.0 Hz, 1H), 4.65 (dd, $J = 11.5$, 2.5 Hz, 1H), 5.13 (ddd, $J = 6.0$, 2.5, 2.0 Hz, 1H), 7.25–7.28 (m, 2H), 7.44–7.47 (m, 2H); ^{13}C NMR (CDCl_3) δ 11.85, 18.62, 18.76, 72.08, 73.55, 97.31, 121.69, 128.98, 131.47, 142.63, 210.12. HRMS (APCI) calcd for $\text{C}_{19}\text{H}_{30}\text{BrOSi}$ $[\text{M}+\text{H}]^+$: 381.1244. Found: 381.1241.

1-(4-Iodophenyl)-2-triisopropylsilyl-2,3-butadien-1-ol (7g):

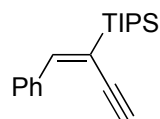
 IR (neat) 3420, 2944, 2864, 1923, 1587, 1482 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.97 (d, $J = 7.0$ Hz, 9H), 1.07 (d, $J = 7.5$ Hz, 9H), 1.13–1.21 (m, 3H), 2.21 (d, $J = 6.0$ Hz, 1H), 4.59 (dd, $J = 11.5$, 2.0 Hz, 1H), 4.64 (dd, $J = 11.5$, 2.5 Hz, 1H), 5.11 (ddd, $J = 6.0$, 2.5, 2.0 Hz, 1H), 7.12–7.15 (m, 2H), 7.64–7.67 (m, 2H); ^{13}C NMR (CDCl_3) δ 11.85, 18.63, 18.77, 72.17, 73.54, 97.37, 128.53, 129.22, 137.43, 143.31, 210.16. HRMS (APCI) calcd for $\text{C}_{19}\text{H}_{30}\text{IOSi}$ $[\text{M}+\text{H}]^+$: 429.1105. Found: 429.1104.

1-(2,6-Dimethylphenyl)-2-triisopropylsilyl-2,3-butadien-1-ol (7h):

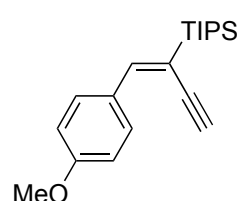
IR (nujol) 3510, 2956, 2864, 1926 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.07 (d, J = 7.0 Hz, 9H), 1.13 (d, J = 7.5 Hz, 9H), 1.26–1.35 (m, 3H), 1.95 (d, J = 5.0 Hz, 1H), 2.40 (s, 6H), 4.22 (dd, J = 11.0, 4.0 Hz, 1H), 4.26 (dd, J = 11.0, 4.0 Hz, 1H), 5.78–5.81 (m, 1H), 6.96–6.99 (m, 2H), 7.02–7.06 (m, 1H); ^{13}C NMR (CDCl_3) δ 12.24, 18.86, 18.97, 21.12, 70.75, 71.09, 94.63, 127.20, 129.08, 136.64, 139.22, 209.92. HRMS (ESI) Calcd for $\text{C}_{21}\text{H}_{35}\text{OSi}$: m/z 331.2452 $[\text{M}+\text{H}]^+$, found: 331.2437 $[\text{M}+\text{H}]^+$.

1-(2-Thienyl)-2-triisopropylsilyl-2,3-butadien-1-ol (7j):

IR (neat) 3427, 2944, 2865, 1925, 1464, 1383 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.99 (d, J = 7.5 Hz, 9H), 1.08 (d, J = 7.5 Hz, 9H), 1.16–1.25 (m, 3H), 2.36 (d, J = 7.5 Hz, 1H), 4.70 (dd, J = 11.5, 2.0 Hz, 1H), 4.75 (dd, J = 11.5, 2.0 Hz, 1H), 5.33–5.37 (m, 1H), 6.94 (dd, J = 5.0, 3.5 Hz, 1H), 7.02 (dd, J = 3.5, 1.0, 1.0 Hz, 1H), 7.24 (dd, J = 5.0, 1.0 Hz, 1H); ^{13}C NMR (CDCl_3) δ 11.80, 18.54, 18.72, 67.97, 74.31, 97.99, 125.51, 125.57, 126.63, 148.49, 210.06. HRMS (APCI) calcd for $\text{C}_{17}\text{H}_{28}\text{OSSi}$ $[\text{M}+\text{H}]^+$: 309.1703. Found: 309.1696.

(E)-1-Phenyl-2-triisopropylsilyl-1-buten-3-yne (8a):

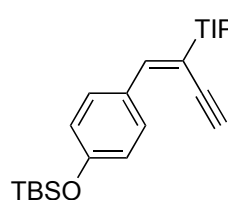
IR (neat) 3308, 2944, 2865, 2074, 1559, 1493, 1464, 1447 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.14 (d, J = 7.0 Hz, 18H), 1.39 (sept, J = 7.0 Hz, 3H), 3.60 (d, J = 1.0 Hz, 1H), 6.89 (s, 1H), 7.28–7.32 (m, 1H), 7.35–7.39 (m, 2H), 7.96–7.99 (m, 2H); ^{13}C NMR (CDCl_3) δ 11.26, 18.65, 85.46, 88.47, 118.27, 128.37, 128.79, 129.05, 137.71, 149.06. HRMS (EI^+) (m/z) calcd for $\text{C}_{19}\text{H}_{28}\text{Si}$: 284.1960. Found: 284.1953.

(E)-1-(4-Methoxyphenyl)-2-triisopropylsilyl-1-buten-3-yne (8b):

IR (nujol) 3310, 3279, 2954, 2864, 2073, 1928, 1604, 1583, 1508 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.14 (d, J = 7.5 Hz, 18H), 1.37 (sept, J = 7.5 Hz, 3H), 3.57

(d, $J = 1.0$ Hz, 1H), 3.83 (s, 3H), 6.81 (s, 1H), 6.88–6.91 (m, 2H), 7.95–7.98 (m, 2H); ^{13}C NMR (CDCl_3) δ 11.27, 18.67, 55.50, 85.88, 87.68, 113.65, 114.84, 130.65, 130.98, 148.47, 159.91. HRMS (ESI) (m/z) calcd for $\text{C}_{20}\text{H}_{30}\text{OSi}$: 315.2139 ($[\text{M}+\text{H}]^+$). Found: 315.2136 ($[\text{M}+\text{H}]^+$).

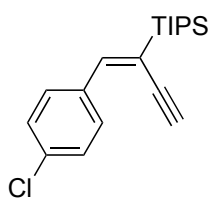
(*E*)-1-(4-*tert*-Butyldimethylsiloxyphenyl)-2-triisopropylsilyl-1-buten-3-yne (8c):



IR (neat) 3311, 2949, 2862, 2071, 1602, 1581, 1505 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.21 (s, 6H), 0.98 (s, 9H), 1.13 (d, $J = 7.5$ Hz, 18H), 1.37 (sept, $J = 7.5$ Hz, 3H), 3.58 (d, $J = 1.0$ Hz, 1H), 6.80 (s, 1H), 6.81–6.84 (m, 2H), 7.89–7.92 (m, 2H); ^{13}C NMR (CDCl_3) δ -4.19, 11.28, 18.44, 18.68, 25.86,

85.88, 87.86, 114.84, 119.91, 130.62, 131.49, 148.60, 156.28. HRMS (APCI) calcd for $\text{C}_{25}\text{H}_{43}\text{OSi}_2$ $[\text{M}+\text{H}]^+$: 415.2847. Found: 415.2843.

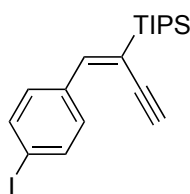
(*E*)-1-(4-Chlorophenyl)-2-triisopropylsilyl-1-buten-3-yne (8e):



IR (neat) 3307, 2944, 2889, 2074, 1489, 1465 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.14 (d, $J = 7.5$ Hz, 18H), 1.38 (sept, $J = 7.5$ Hz, 3H), 3.64 (d, $J = 1.0$ Hz, 1H), 6.83 (s, 1H), 7.31–7.34 (m, 2H), 7.89–7.92 (m, 2H); ^{13}C NMR (CDCl_3) δ 11.22, 18.63, 85.16, 89.21, 119.28, 128.52, 130.28, 134.23, 136.09, 147.48. HRMS

(EI^+) (m/z) calcd for $\text{C}_{19}\text{H}_{27}\text{ClSi}$: 318.1571. Found: 318.1577.

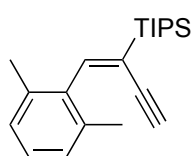
(*E*)-1-(4-Iodophenyl)-2-triisopropylsilyl-1-buten-3-yne (8g):



IR (neat) 3309, 2944, 2865, 2074, 1580, 1482 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.13 (d, $J = 7.5$ Hz, 18H), 1.37 (sept, $J = 7.5$ Hz, 3H), 3.65 (d, $J = 1.0$ Hz, 1H), 6.79 (d, $J = 1.0$ Hz, 1H), 7.70 (s, 4H); ^{13}C NMR (CDCl_3) δ 11.21, 18.63, 85.11, 89.54, 94.45, 119.82, 130.65, 137.02, 137.48, 147.64. HRMS (EI^+) (m/z)

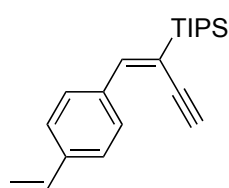
calcd for $\text{C}_{19}\text{H}_{27}\text{ISi}$: 410.0927. Found: 410.0919.

(*E*)-1-(2,6-Dimethylphenyl)-2-triisopropylsilyl-1-buten-3-yne (8h):



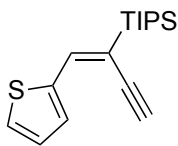
IR (nujol) 3307, 2955, 2078, 1559 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.18 (d, $J = 7.5$ Hz, 18H), 1.38 (sept, $J = 7.5$ Hz, 3H), 2.29 (s, 6H), 3.08 (d, $J = 1.0$ Hz, 1H), 7.03–7.12 (m, 4H); ^{13}C NMR (CDCl_3) δ 11.27, 18.70, 20.81, 84.58, 84.94, 123.37, 127.23, 127.34, 135.52, 138.35, 151.54. HRMS (ESI) Calcd for $\text{C}_{21}\text{H}_{33}\text{Si}$: m/z 313.2346 $[\text{M}+\text{H}]^+$, found: 313.2333 $[\text{M}+\text{H}]^+$.

(E)-1-(4-Vinylphenyl)-2-triisopropylsilyl-1-buten-3-yne (8i):



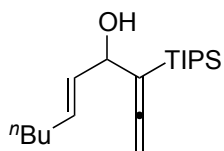
IR (neat) 3307, 2944, 2865, 2073, 1506, 1464 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.14 (d, $J = 7.5$ Hz, 18H), 1.39 (sept, $J = 7.5$ Hz, 3H), 3.63 (d, $J = 1.0$ Hz, 1H), 5.27 (dd, $J = 11.0, 0.5$ Hz, 1H), 5.78 (dd, $J = 17.5, 0.5$ Hz, 1H), 6.72 (dd, $J = 17.5, 10.5$ Hz, 1H), 6.87 (s, 1H), 7.39–7.43 (m, 2H), 7.93–7.96 (m, 2H); ^{13}C NMR (CDCl_3) δ 11.26, 18.65, 85.61, 88.81, 114.53, 118.23, 126.18, 129.28, 136.62, 137.25, 137.92, 148.53. HRMS (ESI) calcd for $\text{C}_{21}\text{H}_{31}\text{Si}$: m/z 311.2190 $[\text{M}+\text{H}]^+$. Found: 311.2177 $[\text{M}+\text{H}]^+$.

(E)-1-(2-Thienyl)-2-triisopropylsilyl-1-buten-3-yne (8j):



IR (neat) 3309, 2944, 2889, 2071, 1560, 1465 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.13 (d, $J = 7.5$ Hz, 18H), 1.36 (sept, $J = 7.5$ Hz, 3H), 3.79 (d, $J = 1.0$ Hz, 1H), 7.04 (dd, $J = 5.0, 4.0$ Hz, 1H), 7.09 (dd, $J = 1.0, 1.0$ Hz, 1H), 7.33 (ddd, $J = 5.0, 1.0, 1.0$ Hz, 1H), 7.37 (ddd, $J = 4.0, 1.0, 1.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 11.29, 18.64, 86.12, 91.16, 114.79, 126.43, 127.07, 129.88, 141.88, 142.57. HRMS (APCI) calcd for $\text{C}_{17}\text{H}_{27}\text{SSi}_2$ $[\text{M}+\text{H}]^+$: 291.1597. Found: 291.1595.

3-Triisopropylsilyl-1,2,5-decatrien-4-ol (9a):



IR (neat) 3447, 2944, 2890, 1923, 1465 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.89 (t, $J = 7.5$ Hz, 3H), 1.07 (d, $J = 7.5$ Hz, 9H), 1.09 (d, $J = 7.5$ Hz, 9H), 1.16–1.26 (m, 3H), 1.28–1.39 (m, 4H), 1.81 (br s, 1H), 2.01–2.07 (m, 2H), 4.46–4.49

(m, 1H), 4.59 (dd, $J = 11.5, 2.0$ Hz, 1H), 4.63 (dd, $J = 11.5, 2.0$ Hz, 1H), 5.54 (ddt, $J = 15.0, 7.5, 1.5$ Hz, 1H), 5.66 (dtd, $J = 15.0, 6.5, 0.5$ Hz, 1H); ^{13}C NMR (CDCl_3) d 11.79, 14.12, 18.80 (two signals merged), 22.42, 31.34, 31.94, 71.05, 72.93, 96.64, 132.41, 132.52, 209.81. HRMS (APCI) calcd for $\text{C}_{19}\text{H}_{37}\text{OSi}$ $[\text{M}+\text{H}]^+$: 309.2608. Found: 309.2606.

1-Phenyl-4-triisopropylsilyl-1,4,5-hexatrien-3-ol (9b):

IR (nujol) 3323, 2954, 1923 cm^{-1} ; ^1H NMR (CDCl_3) d 1.09 (d, $J = 7.5$ Hz, 9H), 1.11 (d, $J = 7.5$ Hz, 9H), 1.20–1.30 (m, 3H), 1.92 (br d, $J = 4.5$ Hz, 1H), 4.63 (dd, $J = 11.5, 2.0$ Hz, 1H), 4.68 (dd, $J = 11.5, 2.0$ Hz, 1H), 4.69–4.73 (m, 1H), 6.30 (dd, $J = 15.5, 7.0$ Hz, 1H), 6.58 (d, $J = 15.5$ Hz, 1H), 7.22–7.26 (m, 1H), 7.29–7.34 (m, 2H), 7.37–7.40 (m, 2H); ^{13}C NMR (CDCl_3) d 11.83, 18.82, 18.84, 71.02, 73.20, 96.40, 126.77, 127.82, 128.73, 130.44, 131.97, 136.92, 210.20. HRMS (APCI) calcd for $\text{C}_{21}\text{H}_{33}\text{OSi}$ $[\text{M}+\text{H}]^+$: 329.2295. Found: 329.2290.

6-Phenyl-3-triisopropylsilyl-(3E,5E)-hexadien-1-yne (10a):

IR (neat) 3312, 2944, 2890, 2074, 1632, 1545, 1465 cm^{-1} ; ^1H NMR (CDCl_3) d 0.91 (t, $J = 7.5$ Hz, 3H), 1.09 (d, $J = 7.0$ Hz, 18H), 1.22–1.31 (m, 3H), 1.32–1.38 (m, 2H), 1.38–1.45 (m, 2H), 2.18 (tdd, $J = 7.0, 7.0, 1.5$ Hz, 2H), 3.40 (d, $J = 1.0$ Hz, 1H), 5.93 (dtd, $J = 15.0, 7.0, 0.5$ Hz, 1H), 6.62 (d, $J = 10.5$ Hz, 1H), 6.77 (ddt, $J = 15.0, 10.5, 1.5$ Hz, 1H); ^{13}C NMR (CDCl_3) d 11.22, 14.15, 18.65, 22.58, 31.44, 32.78, 84.93, 85.42, 116.43, 129.46, 139.70, 151.70. HRMS (ESI) Calcd for $\text{C}_{19}\text{H}_{34}\text{Si}$: m/z 291.2503 $[\text{M}+\text{H}]^+$, found: 291.2496 $[\text{M}+\text{H}]^+$.

6-Phenyl-3-triisopropylsilyl-(3E,5E)-hexadien-1-yne (10b):

IR (neat) 3309, 3029, 2944, 2865, 2072, 1615, 1539 cm^{-1} ; ^1H NMR (CDCl_3) d 1.12 (d, $J = 7.5$ Hz, 18H), 1.33 (sept, $J = 7.5$ Hz, 3H), 3.56 (d, $J = 1.0$ Hz, 1H), 6.73 (d, $J = 15.5$ Hz, 1H), 6.82 (ddd, $J = 10.5, 1.0, 1.0$ Hz, 1H), 7.24–7.28 (m,

1H), 7.31–7.35 (m, 2H), 7.47–7.50 (m, 2H); ^{13}C NMR (CDCl_3) δ 11.26, 18.65, 84.90, 87.26, 120.38, 127.19, 127.47, 128.41, 128.83, 135.67, 137.14, 151.00. HRMS (ESI) Calcd for $\text{C}_{21}\text{H}_{31}\text{Si}$: m/z 311.2190 $[\text{M}+\text{H}]^+$, found: 311.2180 $[\text{M}+\text{H}]^+$.

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9. *E*-**10d**: R_f (hexane) = 0.35. *Z*-**10d**: R_f (hexane) = 0.55.

Appendix

Copper-Catalyzed Reaction of Alkyl Halides with Cyclopentadienylmagnesium Reagent

Treatment of alkyl halides, including tertiary alkyl bromides, with cyclopentadienylmagnesium bromide in the presence of a catalytic amount of copper(II) triflate yields the corresponding cyclopentadienylated products in high yields. The following hydrogenation of the products provides alkyl-substituted cyclopentanes.

Introduction

Copper-catalyzed reactions of alkyl halides with organometallic reagents are among the most useful carbon–carbon bond forming reactions in organic synthesis.¹ Whereas copper-catalyzed reactions of primary alkyl halides have been well-established, there are few examples of copper-catalyzed reactions of secondary^{1d} and tertiary alkyl halides with organometallic reagents that create tertiary quaternary carbons.² In this Chapter, the author reports that the cyclopentadienyl Grignard reagent reacts with tertiary alkyl halides under copper catalysis to afford the corresponding coupling products.

Results and Discussion

Treatment of 2-methyl-2-bromodecane (**1a**) with cyclopentadienylmagnesium bromide in the presence of a catalytic amount of copper(II) triflate in diisopropyl ether afforded a mixture of the corresponding coupling products **3a** and **3a'** in high combined yield. Initially formed **2a** would undergo isomerization into **3a** and **3a'** because of the high acidity of the hydrogen on the cyclopentadienyl ring. In order to simplify the analysis of the products,³ the products were subjected to hydrogenation with the aid of platinum oxide in boiling acetic acid.⁴ As a result, cyclopentyl-substituted product **4a** was obtained in 85% overall yield (Scheme 1).

The choice of solvent is crucial to attain high yield (Table 1). Bulky ethers such as diisopropyl ether and *t*-butyl methyl ether were suitable solvents (Table 1, entries 1 and 2). Toluene that had no heteroatoms was comparable to diisopropyl ether (Table 1, entry 3). The reactions in widely used diethyl ether, THF, and dioxane were sluggish (Table 1, entries 4–6). Cyclopentyl methyl ether and dibutyl ether also failed to serve as the solvent (Table 1, entries 7 and 8). Thus, less coordinating solvents afforded higher combined yields of **3a** and **3a'**. A variety of copper salts showed the catalytic activity. Copper(II) fluoride is an alternative catalyst, albeit with lower efficiency (Table 1, entry 9). Copper(II) chloride was less efficient

(Table 1, entry 10). Not only copper(II) halides but also copper(I) halides exhibited modest catalytic activity (Table 1, entries 11–13). Other copper salts such as copper(I) acetate and cyanide exhibited low catalytic activity (Table 1, entries 14 and 15). Silver(I) nitrate, which was effective in the cross-coupling reaction of tertiary alkyl halides with allyl or benzyl Grignard reagent,^{2c} was less effective than copper(II) triflate (Table 1, entry 17).

Scheme 1.

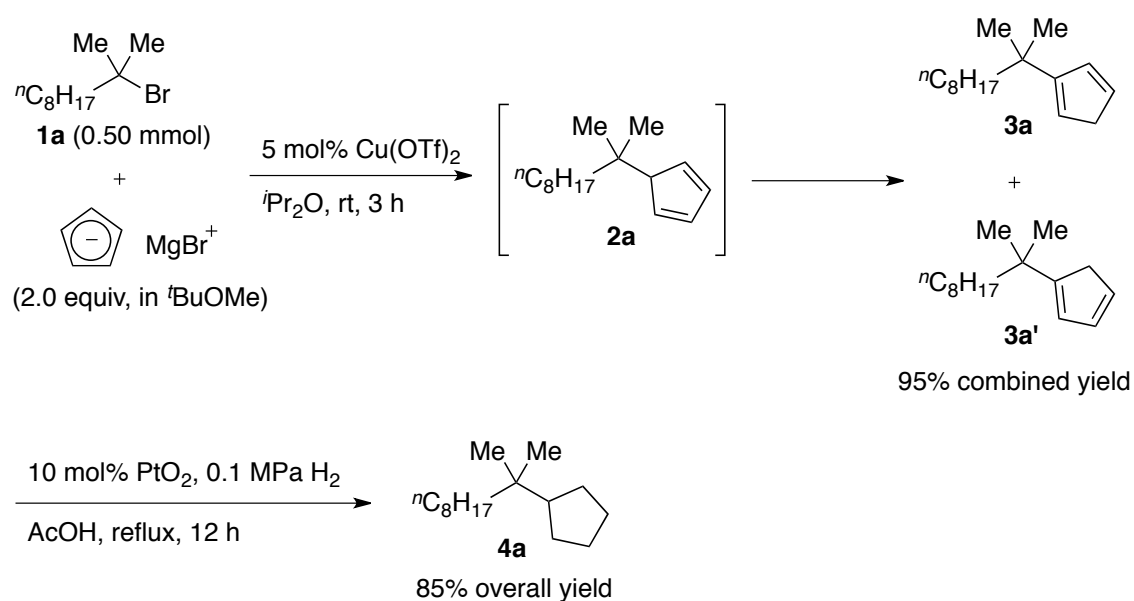
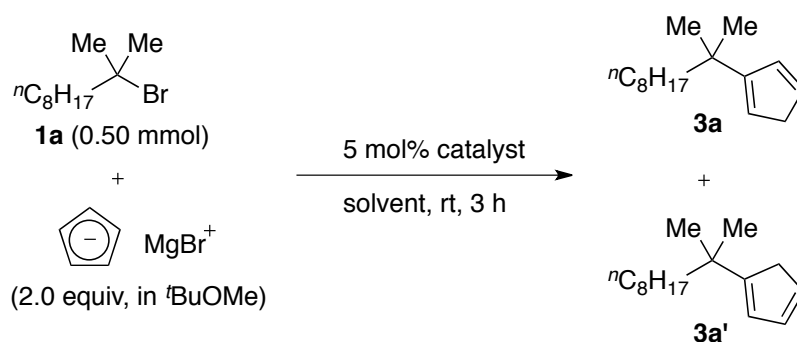
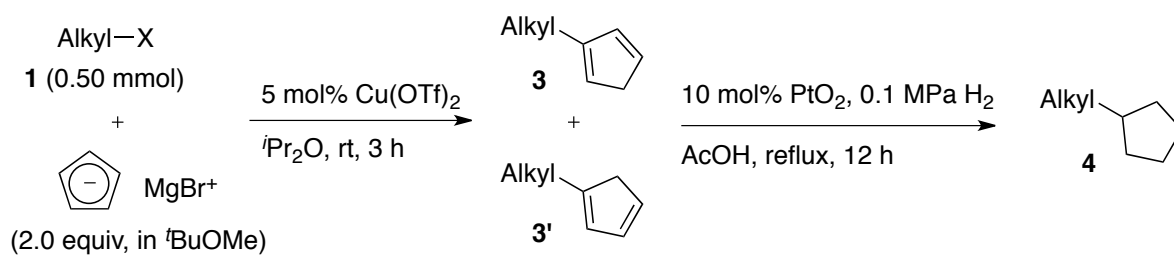


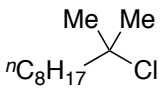
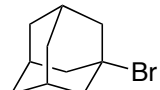
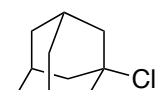
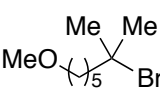
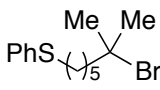
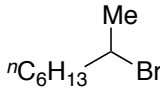
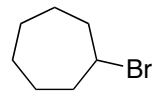
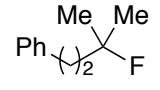
Table 1. Solvent Effect and Catalyst Screening

entry	solvent	catalyst	combined yield (%) ^a
1	<i>i</i> Pr ₂ O	Cu(OTf) ₂	96 (95) ^b
2	<i>t</i> BuOMe	Cu(OTf) ₂	68
3	toluene	Cu(OTf) ₂	90
4	Et ₂ O	Cu(OTf) ₂	16
5	1,4-dioxane	Cu(OTf) ₂	12
6	THF	Cu(OTf) ₂	15
7	<i>n</i> C ₅ H ₉ OMe	Cu(OTf) ₂	13
8	<i>n</i> Bu ₂ O	Cu(OTf) ₂	22
9	<i>i</i> Pr ₂ O	CuF ₂	77
10	<i>i</i> Pr ₂ O	CuCl ₂	59
11	<i>i</i> Pr ₂ O	CuCl	44
12	<i>i</i> Pr ₂ O	CuBr	57
13	<i>i</i> Pr ₂ O	CuI	31
14	<i>i</i> Pr ₂ O	CuOAc	30
15	<i>i</i> Pr ₂ O	CuCN	26
16	<i>i</i> Pr ₂ O	CuOTf · 0.5C ₆ H ₆	27
17	<i>i</i> Pr ₂ O	AgNO ₃	26

^a Determined by ¹H NMR analysis. ^b Isolated yield.

Having established the optimal conditions, we explored the scope of the reaction (Table 2). Not only alkyl bromide **1a** but also the corresponding chloride **1a-Cl** reacted smoothly with CpMgBr (Table 2, entry 1). The reactions of 1-haloadamantane required a higher temperature and a prolonged reaction time (Table 2, entries 2 and 3). Gratifyingly, a phenylsulfanyl group as well as a methoxyl group was compatible without deactivating the copper catalyst (Table 2, entries 4 and 5). Unfortunately, the following hydrogenation of **3d** and **3d'** proceeded inefficiently, although the reaction conditions were not optimized for the sulfur-containing substrate. The reactions of secondary alkyl halides were moderate (Table 2, entries 6 and 7). The reaction of primary alkyl bromide **1g** was sluggish (Table 2, entry 8). Interestingly, tertiary alkyl fluoride **1h** participated in the cyclopentadienylation (Table 2, entry 9).

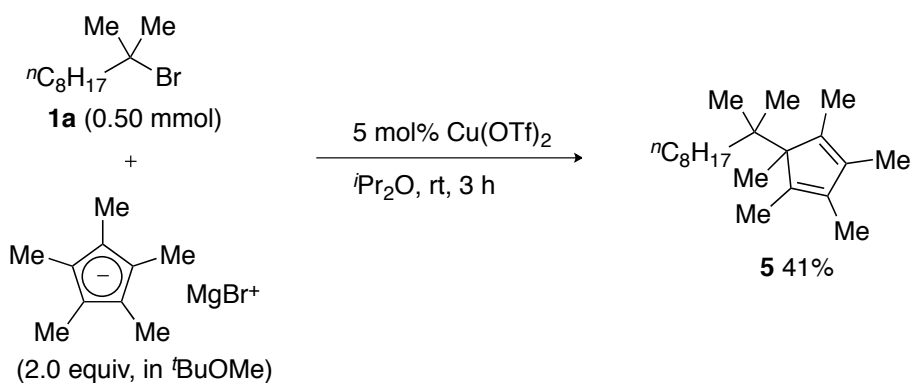
Table 2. Copper-Catalyzed Cyclopentadienylation of Alkyl Halides Followed by Hydrogenation

entry	substrate 1	Combined yield of 3 and 3' (%) ^a	4	yield of 4 from 1 (%) ^a
1	 1a-Cl	88	4a	80
2	 1b	94	4b	83
3	 1b-Cl	95	4b	83
4	 1c	90	4c	84
5	 1d	95	4d	50
6 ^b	 1e	51	4e	49
7 ^b	 1f	77	4f	52
8 ^b	ⁿ C ₉ H ₁₉ -Br	(32) ^c	4g	25
9 ^d	 1h	69	4h	61

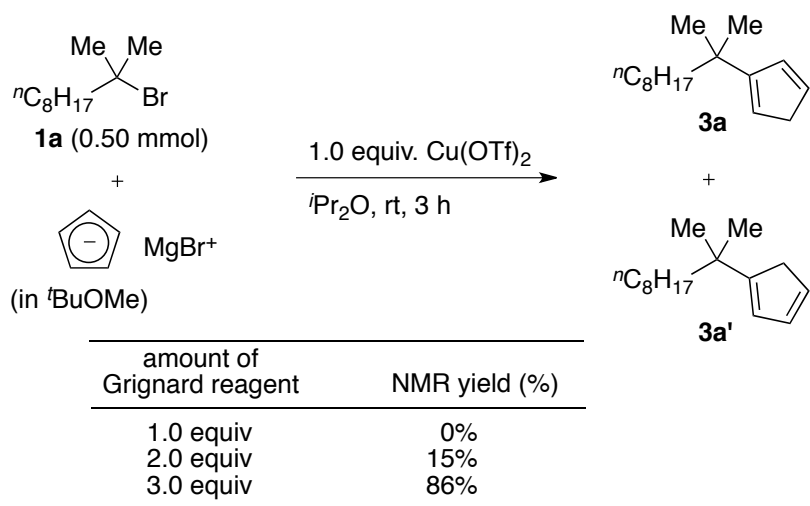
^a Yield is of isolated product. ^b At reflux for 6 h. ^c Determined by ¹H NMR analysis. ^d For 6 h.

The copper-catalyzed reaction of **1a** with pentamethylcyclopentadienylmagnesium bromide in refluxing diisopropyl ether afforded the corresponding coupling product **5** in 41% yield (Scheme 2). This reaction provides a rare example of construction of two adjacent quaternary carbon centers.

Scheme 2.



To gain information about the reaction mechanism, the reactions of **1a** with stoichiometric copper reagents were examined with varying amounts of CpMgBr (Scheme 3). Treatment of **1a** (0.50 mmol) with a copper complex, prepared from 0.50 mmol of $\text{Cu}(\text{OTf})_2$ and 0.50 mmol of CpMgBr , did not provide **3a** and **3a'** with complete recovery of **1a**. Most of **1a** remained unchanged when **1a** was treated with a copper reagent, prepared from 0.50 mmol of $\text{Cu}(\text{OTf})_2$ and 1.0 mmol of CpMgBr . A reagent generated from 0.50 mmol of $\text{Cu}(\text{OTf})_2$ and 1.5 mmol of CpMgBr dramatically changed the outcome. The desired products were obtained in a high combined yield of 86%. Hence, the copper reagent that is active for this reaction might be $[\text{Cp}_3\text{Cu}]\text{MgBr}^5$ or a more complex cuprate.⁶

Scheme 3.**Conclusion**

The author has developed a copper-catalyzed reaction of tertiary alkyl halides with cyclopentadienyl Grignard reagent. Including the following hydrogenation of the cyclopentadienyl ring with hydrogen under PtO₂ catalysis, the overall transformation represents formal cyclopentylation of tertiary alkyl halides.

Experimental Section

Instrumentation

^1H NMR (500 MHz) and ^{13}C NMR (125.7 MHz) spectra were taken on a Varian UNITY INOVA 500 spectrometer. Chemical shifts (δ) are in parts per million relative to tetramethylsilane at 0.00 ppm for ^1H and relative to CDCl_3 at 77.23 ppm for ^{13}C unless otherwise noted. IR spectra were determined on a SHIMADZU FTIR-8200PC spectrometer. Silica gel (Wakogel 200 mesh) was used for column chromatography. The analyses were carried out at the Elemental Analysis Center of Kyoto University.

Materials

Unless otherwise noted, materials obtained from commercial suppliers were used without further purification.

Experimental Procedures

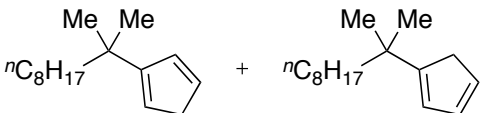
Representative Procedure for Cu-Catalyzed Allylation of Alkyl Halides and Subsequential Hydrogenation.

Compound 4a: Copper(II) triflate (9.0 mg, 0.0025 mmol) was placed in a 30 mL reaction flask under argon. A solution of cyclopentadienylmagnesium bromide (0.86 M in *t*-butyl methyl ether, prepared from cyclopentadiene and *n*-butylmagnesium bromide, 1.16 mL, 1.0 mmol) was then added to the flask. Substrate **1a** (118 mg, 0.50 mmol) in diisopropyl ether (4.0 mL) was added. After being stirred for 3 h at 25 °C, the reaction mixture was poured into a saturated ammonium chloride solution (10 mL). The products were extracted with hexane (10 mL \times 3). The combined organic layer was dried over Na_2SO_4 and concentrated. Silica gel column purification (hexane) of the crude product provided a mixture of **3a** and **3a'** (105 mg, 0.47 mmol) in 95% combined yield. Platinum oxide (11 mg, 0.047 mmol) was placed in a 30 mL reaction flask.

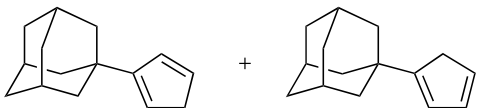
The flask was filled with argon first, and then with hydrogen. The mixture of **3a** and **3a'** (105 mg, 0.47 mmol) in acetic acid (10 mL) was added, and the resulting mixture was heated for 12 h. After being cooled to room temperature, the mixture was filtered through a pad of Celite. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel to afford **4a** (96mg, 0.43 mmol) in 85% overall yield.

Characterization Data of New Compounds

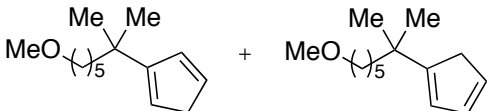
2-(1,4-Cyclopentadienyl)-2-methyldecane/2-(1,3-cyclopentadienyl)-2-methyldecane (**3a/3a'**):


 $^1\text{H NMR}$ (CDCl_3) δ 0.87 (t, $J = 7.0$ Hz, 3H), 1.07–1.15 (m, 2H), 1.14 (s, 6H), 1.19–1.31 (m, 10H), 1.41–1.44 (m, 2H), 2.87–2.89 (m, $0.91 \times 2\text{H}$), 2.94–2.95 (m, $0.09 \times 2\text{H}$), 5.94–5.96 (m, $0.09 \times 1\text{H}$), 6.13–6.14 (m, $0.91 \times 1\text{H}$), 6.25–6.27 (m, $0.91 \times 1\text{H}$), 6.40–6.42 (m, 1H), 6.55–6.56 (m, $0.09 \times 1\text{H}$); $^{13}\text{C NMR}$ (CDCl_3) for major isomer δ 14.30, 22.86, 25.00, 28.85, 29.56, 29.80, 30.62, 32.10, 36.47, 40.34, 44.09, 124.97, 130.61, 132.17, 158.73.

1-(1,4-Cyclopentadienyl)adamantine/1-(1,3-cyclopentadienyl)adamantine (**3b/3b'**):

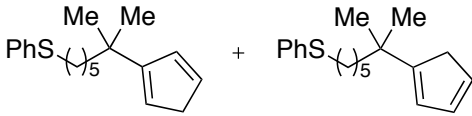

 $^1\text{H NMR}$ (CDCl_3) δ 1.68–1.79 (m, 12H), 2.02 (br s, 3H), 2.93–2.95 (m, 2H), 5.93–5.95 (m, $0.55 \times 1\text{H}$), 6.14–6.15 (m, $0.45 \times 1\text{H}$), 6.26–6.28 (m, $0.45 \times 1\text{H}$), 6.41–6.46 (m, 1H), 6.64–6.66 ($0.55 \times 1\text{H}$); $^{13}\text{C NMR}$ (CDCl_3) for a mixture of isomers δ 28.74, 28.93, 34.21, 35.32, 37.13, 37.15, 39.17, 41.07, 42.24, 43.56, 122.54, 123.16, 130.35, 132.06, 132.31, 133.56, 157.57, 160.72.

2-(1,4-Cyclopentadienyl)-7-methoxy-2-methylheptane/2-(1,4-cyclopentadienyl)-7-methoxy-2-methylheptane (**3c/3c'**):

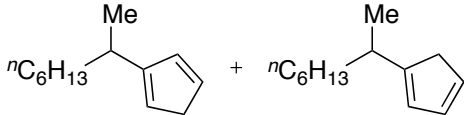

 $^1\text{H NMR}$ (CDCl_3) δ 1.09–1.16 (m, 2H), 1.14 (s, 6H), 1.24–1.30 (m, 2H), 1.42–1.46 (m, 2H), 1.50–1.57 (m,

2H), 2.87–2.88 (0.95 × 2H), 2.94–2.95 (m, 0.05 × 2H), 3.31 (s, 3H), 3.33 (t, $J = 7.0$ Hz, 2H), 5.93–5.96 (m, 0.05 × 1H), 6.13–6.14 (m, 0.95 × 1H), 6.25–6.27 (m, 0.95 × 1H), 6.40–6.44 (m, 1H), 6.54–6.56 (m, 0.05 × 1H); ^{13}C NMR (CDCl_3) for major isomer δ 24.84, 27.03, 28.83, 29.81, 36.44, 40.32, 43.95, 58.72, 73.10, 125.05, 130.67, 132.15, 158.53.

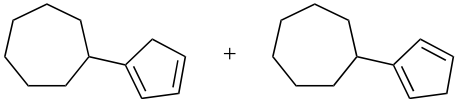
2-(1,4-Cyclopentadienyl)-2-methyl-7-phenylsulfanylheptane/2-(1,3-cyclopentadienyl)-2-methyl-7-phenylsulfanylheptane (3d/3d'):

 ^1H NMR (CDCl_3) δ 1.09–1.16 (m, 2H), 1.13 (s, 6H), 1.33–1.39 (m, 2H), 1.41–1.45 (m, 2H), 1.58–1.64 (m, 2H), 2.86–2.89 (m, 2H), 2.88 (t, $J = 7.5$ Hz, 2H), 5.94–5.95 (m, 0.04 × 1H), 6.12–6.13 (m, 0.96 × 1H), 6.25–6.27 (m, 0.96 × 1H), 6.40–6.42 (m, 1H), 6.53–6.55 (m, 0.04 × 1H), 7.14–7.18 (m, 1H), 7.25–7.33 (m, 4H); ^{13}C NMR (CDCl_3) for major isomer δ 24.57, 28.82, 29.33, 29.72, 33.78, 36.43, 40.34, 43.87, 125.12, 125.83, 128.99, 129.07, 130.69, 132.15, 137.18, 158.38.

2-(1,4-Cyclopentadienyl)octane/2-(1,3-cyclopentadienyl)octane (3e/3e'):

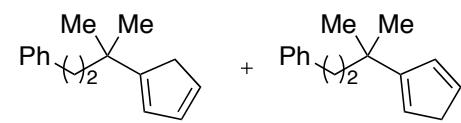
 ^1H NMR (CDCl_3) δ 0.88 (t, $J = 7.0$ Hz, 3H), 1.12 (d, $J = 7.0$ Hz, 0.43 × 3H), 1.12 (d, $J = 7.0$ Hz, 0.57 × 3H), 1.20–1.32 (m, 8H), 1.35–1.45 (m, 1H), 1.45–1.56 (m, 1H), 2.48–2.60 (m, 1H), 2.87–2.88 (m, 0.43 × 2H), 2.92–2.96 (m, 0.57 × 2H), 5.97–5.98 (m, 0.57 × 1H), 6.14–6.15 (m, 0.43 × 1H), 6.25–6.27 (m, 0.43 × 1H), 6.40–6.44 (m, 1H), 6.49–6.51 (m, 0.57 × 1H); ^{13}C NMR (CDCl_3) for a mixture of isomers δ 14.29, 20.37, 21.40, 22.82, 22.87, 27.32, 27.59, 27.63, 29.66, 32.06, 32.23, 34.36, 34.60, 35.29, 36.71, 37.76, 41.01, 41.09, 124.57, 125.30, 130.39, 132.38, 133.60, 133.68, 152.87, 155.75.

(1,4-Cyclopentadienyl)cycloheptane/(1,3-cyclopentadienyl)cycloheptane (3f/3f'):

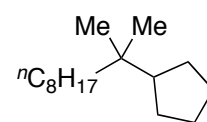
 ^1H NMR (CDCl_3) δ 1.45–1.76 (m, 10H), 1.77–1.94 (m, 2H), 2.49–2.60 (m, 1H), 2.91–2.92 (m, 0.40 × 2H),

2.93–2.94 (m, $0.60 \times 2\text{H}$), 5.95–5.97 (m, $0.60 \times 1\text{H}$), 6.13–6.14 (m, $0.40 \times 1\text{H}$), 6.24–6.25 (m, $0.40 \times 1\text{H}$), 6.40–6.43 (m, 1H), 6.49–6.51 (m, $0.60 \times 1\text{H}$); ^{13}C NMR (CDCl_3) for a mixture of isomers δ 26.66, 26.82, 28.46, 28.47, 35.54, 35.68, 40.86, 41.07, 41.81, 41.82, 123.37, 124.21, 130.22, 132.39, 133.67, 134.29, 153.94, 156.91.

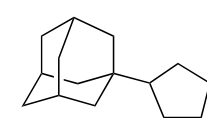
2-(1,4-Cyclopentadienyl)-2-methyl-4-phenylbutane/2-(1,3-cyclopentadienyl)-2-methyl-4-phenylbutane (3h/3h'):

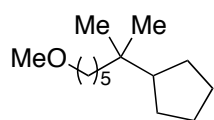
 ^1H NMR (CDCl_3) δ 1.23 (s, 6H), 1.74–1.79 (m, 2H), 2.41–2.45 (m, 2H), 2.93–2.95 (m, $0.90 \times 2\text{H}$), 2.98–3.00 (m, $0.10 \times 2\text{H}$), 6.02–6.05 (m, $0.10 \times 1\text{H}$), 6.22–6.24 (m, $0.90 \times 1\text{H}$), 6.29–6.31 (m, $0.90 \times 1\text{H}$), 6.43–6.47 (m, 1H), 6.60–6.63 (m, $0.10 \times 1\text{H}$), 7.12–7.17 (m, 3H), 7.24–7.27 (m, 2H); ^{13}C NMR (CDCl_3) for major isomer δ 28.82, 31.65, 36.69, 40.36, 46.12, 125.61, 125.73, 128.42, 128.48, 130.89, 132.17, 143.42, 157.76

2-Cyclopentyl-2-methyldecane (4a):

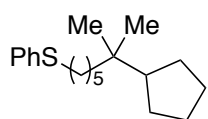
 IR (neat) 2929, 2857, 1558, 1507, 1472, 1465, 1457, 1386, 1364 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.79 (s, 6H), 0.88 (t, $J = 7.0$ Hz, 3H), 1.14–1.33 (m, 16H), 1.45–1.57 (m, 6H), 1.67–1.74 (m, 1H); ^{13}C NMR (CDCl_3) δ 14.32, 22.90, 24.11, 24.64, 26.02, 27.03, 29.60, 29.94, 31.00, 32.15, 34.57, 42.04, 49.51. Found: C, 85.86; H, 14.27%. Calcd for $\text{C}_{16}\text{H}_{32}$: C, 85.63; H, 14.37%.

1-Cyclopentyladamantane (4b):

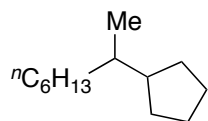
 IR (neat) 2903, 2847, 1559, 1507, 1456, 1448, 1437 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.24–1.31 (m, 2H), 1.40–1.54 (m, 12H), 1.60–1.72 (m, 7H), 1.93 (br s, 3H); ^{13}C NMR (CDCl_3) δ 25.49, 25.91, 28.93, 34.12, 37.72, 40.67, 51.77. Found: C, 88.44; H, 11.87%. Calcd for $\text{C}_{15}\text{H}_{24}$: C, 88.16; H, 11.84%.

2-Cyclopentyl-7-methoxy-2-methylheptane (4c):

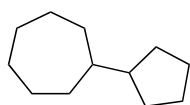
IR (neat) 2936, 2867, 1558, 1507, 1472, 1457, 1387, 1121 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.78 (s, 6H), 1.17–1.32 (m, 8H), 1.44–1.61 (m, 8H), 1.66–1.73 (m, 1H), 3.33 (s, 3H), 3.36 (t, $J = 7.0$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 23.96, 24.61, 26.00, 27.00, 27.38, 29.94, 34.55, 41.90, 49.48, 58.74, 73.20. Found: C, 78.96; H, 13.07%. Calcd for $\text{C}_{14}\text{H}_{28}\text{O}$: C, 79.18; H, 13.29%.

2-Cyclopentyl-2-methyl-7-phenylsulfanylheptane (4d):

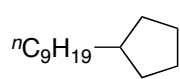
IR (neat) 2934, 2866, 1684, 1653, 1559, 1507, 1473, 1364, 736 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.78 (s, 6H), 1.15–1.28 (m, 6H), 1.35–1.41 (m, 2H), 1.46–1.57 (m, 6H), 1.63–1.70 (m, 3H), 2.92 (t, $J = 7.5$ Hz, 2H), 7.15–7.18 (m, 1H), 7.27–7.33 (m, 4H); ^{13}C NMR (CDCl_3) δ 23.65, 24.59, 25.99, 26.99, 29.42, 30.10, 33.76, 34.55, 41.79, 49.46, 125.79, 128.98, 128.99, 137.23. Found: C, 78.59; H, 10.18%. Calcd for $\text{C}_{19}\text{H}_{30}\text{S}$: C, 78.55; H, 10.41%.

2-Cyclopentyl-octane (4e):

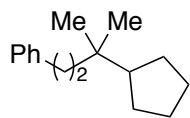
IR (neat) 2954, 2928, 2859, 1559, 1507, 1457, 1377 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.85 (d, $J = 7.0$ Hz, 3H), 0.88 (t, $J = 7.0$ Hz, 3H), 1.02–1.15 (m, 3H), 1.15–1.44 (m, 10H), 1.45–1.53 (m, 2H), 1.54–1.61 (m, 3H), 1.67–1.76 (m, 2H); ^{13}C NMR (CDCl_3) δ 14.32, 17.97, 22.91, 25.64, 25.66, 27.16, 29.95, 30.44, 30.95, 32.17, 35.91, 38.35, 46.60. Found: C, 85.44; H, 14.46%. Calcd for $\text{C}_{13}\text{H}_{26}$: C, 85.63; H, 14.37%.

Cyclopentylcycloheptane (4f):

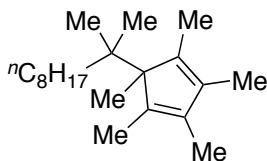
IR (neat) 2925, 2858, 1451, 943 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.05–1.13 (m, 2H), 1.17–1.31 (m, 3H), 1.36–1.66 (m, 13H), 1.68–1.76 (m, 4H); ^{13}C NMR (CDCl_3) δ 25.67, 27.03, 28.77, 30.95, 33.31, 45.04, 47.10. Found: C, 86.61; H, 13.54%. Calcd for $\text{C}_{12}\text{H}_{22}$: C, 86.67; H, 13.33%.

1-Cyclopentylnonane (4g):

IR (neat) 2924, 2855, 1559, 1507, 1490, 1457, 1437 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.88 (t, $J = 7.0$ Hz, 3H), 1.02–1.09 (m, 2H), 1.22–1.33 (m, 15H), 1.46–1.62 (m, 5H), 1.69–1.76 (m, 3H); ^{13}C NMR (CDCl_3) δ 14.32, 22.90, 25.40, 29.02, 29.57, 29.86, 29.93, 30.17, 32.13, 32.94, 36.48, 40.39. Found: C, 85.57; H, 14.39%. Calcd for $\text{C}_{14}\text{H}_{28}$: C, 85.63; H, 14.37%.

(3-Cyclopentyl-3-methylbutyl)benzene (4h):

IR (neat) 2955, 2867, 1684, 1653, 1559, 1507, 1457, 1364, 745 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.91 (s, 6H), 1.25–1.32 (m, 2H), 1.49–1.66 (m, 8H), 1.78–1.85 (m, 1H), 2.56–2.60 (m, 2H), 7.16–7.20 (m, 3H), 7.27–7.30 (m, 2H); ^{13}C NMR (CDCl_3) δ 24.59, 26.02, 27.05, 30.87, 34.88, 44.42, 49.41, 125.65, 128.48, 128.52, 144.01. Found: C, 89.09; H, 11.39%. Calcd for $\text{C}_{16}\text{H}_{24}$: C, 88.82; H, 11.18%.

2-Methyl-2-(1,2,3,4,5-pentamethyl-2,4-cyclopentadienyl)decane (5):

IR (neat) 2928, 2857, 1447, 1379, 1362, 1081, 1060, 668 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.83 (s, 6H), 0.88 (t, $J = 7.0$ Hz, 3H), 0.93 (s, 3H), 1.08–1.29 (m, 14H), 1.72 (s, 6H), 1.79 (s, 6H); ^{13}C NMR (CDCl_3) δ 11.30, 14.32, 14.57, 16.50, 22.88, 23.93, 24.67, 29.57, 30.01, 31.06, 32.12, 37.72, 37.87, 62.50, 135.22, 142.83. Found: C, 87.04; H, 13.28%. Calcd for $\text{C}_{21}\text{H}_{38}$: C, 86.82; H, 13.18%.

References and Notes

1. (a) Lipshutz, B. H.; Sengupta, S. *Org. React.* **1992**, *41*, 149. (b) Terao, J.; Ikumi, A.; Kuniyasu, H.; Kambe, N. *J. Am. Chem. Soc.* **2003**, *125*, 5646. (c) Terao, J.; Todo, H.; Begum, S. A.; Kuniyasu, H.; Kambe, N. *Angew. Chem., Int. Ed.* **2007**, *46*, 2086. (d) Burns, D. H.; Miller, J. D.; Chan, H. K.; Delaney, M. O. *J. Am. Chem. Soc.* **1997**, *119*, 2125. (e) Cahiez, G.; Chaboche, C.; Jezequel, M. *Tetrahedron* **2000**, *56*, 2733. (f) Herber, C.; Breit, B. *Eur. J. Org. Chem.* **2007**, 3512.
2. Cobalt and silver are known to catalyze the reactions of tertiary alkyl halides with allyl- or benzylmagnesium reagents: (a) Tsuji, T.; Yorimitsu, H.; Oshima, K. *Angew. Chem., Int. Ed.* **2002**, *41*, 4137. (b) Ohmiya, H.; Yorimitsu, H.; Oshima, K. *Chem.—Eur. J.* **2004**, *10*, 5640. (c) Someya, H.; Ohmiya, H.; Yorimitsu, H.; Oshima, K. *Org. Lett.* **2008**, *10*, 969.
3. Products **3a** and **3a'** underwent smooth dimerization by the Diels-Alder reaction even at room temperature overnight. Thus, the following hydrogenation should be performed immediately.
4. The hydrogenation is not a trivial reaction because of the steric hindrance of the tertiary alkyl group. Initial attempts to reduce the mixture of **3a** and **3a'** in other solvents such as isopropyl alcohol and formic acid under 0.1 MPa of hydrogen failed to attain full conversion.
5. No dicyclopentadienyl (Cp-Cp) was formed upon treatment of Cu(OTf)₂ with 2 equiv of CpMgBr in the absence of organic halide. This fact indicates that the active copper species in the reaction mixture is not Cu^I or Cu⁰ species but Cu^{II}.
6. The author examined some experiments to assess the intermediacy of alkyl radicals in the reaction, which failed to support the intermediacy.

Publication List

I. Parts of the present thesis have been published in the following journals.

- Chapter 1 Allyl-, Allenyl-, and Propargyl-Transfer Reactions through Cleavage of C–C Bonds Catalyzed by an N-Heterocyclic Carbene/Copper Complex: Synthesis of Multisubstituted Pyrroles
Masahiro Sai, Hideki Yorimitsu, and Koichiro Oshima
Angew. Chem., Int. Ed. **2011**, *50*, 3294–3298.
- Chapter 2 Silver-Catalyzed Intramolecular Chloroamination of Allenes: Easy Access to Functionalized 3-Pyrroline and Pyrrole Derivatives
Masahiro Sai and Seijiro Matsubara
Org. Lett. **2011**, *13*, 4676–4679.
- Chapter 3 Li⁺-Catalyzed Nazarov-Type Cyclization of 1-Aryl-2,3-butadien-1-ols: Synthesis of Benzofulvene Derivatives
Masahiro Sai and Seijiro Matsubara
To be submitted.
- Chapter 4 Copper-Catalyzed Stereoselective Synthesis of Functionalized Conjugated Enynes, Dienynes, and Ene-diynes from α -Allenols
Masahiro Sai and Seijiro Matsubara
To be submitted.
- Appendix Copper-Catalyzed Reaction of Alkyl Halides with Cyclopentadienylmagnesium Reagent
Masahiro Sai, Hidenori Someya, Hideki Yorimitsu, and Koichiro Oshima
Org. Lett. **2008**, *10*, 2545–2547.

II. Other publication not included in this thesis.

Copper-Catalyzed Allylation of Alkyl Halides with Allylic Grignard Reagents

Masahiro Sai, Hideki Yorimitsu, and Koichiro Oshima

Bull. Chem. Soc. Jpn. **2009**, 82, 1194-1196.

A Heterogeneous Ru/CeO₂ Catalyst Effective for Transfer-allylation from Homoallyl Alcohols to Aldehydes

Hiroki Miura, Kenji Wada, Saburo Hosokawa, Masahiro Sai, Teruyuki Kondo, and Masashi Inoue

Chem. Commun. **2009**, 4112-4114.

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Masahiro Sai